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OBJECTIVE DETERMINATION OF OPTIMAL POWER LINE DESIGNS

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ABSTRACT

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Title of thesis: OBJECTIVE DETERMINATION OF OPTIMAL POWER LINE DESIGNS

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The thesis investigated the possibility of overhead power line designs being decided by using an objective rather than a subjective method. Power lines are required to meet criteria for load and transfer capability as specified by system planners which results in many different line design solutions. The decision as to which solution to adopt and construct is difficult if a subjective method is used. The hypothesis proposed is thus as follows:

It appears that one or a small set of appropriate technology indicators can be used by network planners and designers to identify the best group of overhead lines to meet specified objectives. These indicators can be used for a wide range of applications for AC and DC lines

The research was performed by investigating the specifications of the planners and determining the different line designs that could complete the work. This was based on actual case studies of lines designed and built in Eskom South Africa. In addition the parameters for AC and DC lines were examined and parameters selected that would best represent the requirements of the planners as well as cover most of the variables involved in line design. These include the conductor, subconductor bundle, the phase spacing for AC and pole spacing for DC, the tower type and the foundation type.

Indicators were derived for both AC and DC line designs using a simple scoring method. An overall score based on weighting factors can be determined for each line design option. By varying the weighting factors the most robust design can be determined. The indicators do not determine the optimum design but rather indicate the group of designs that need to be developed further and implemented. The method is thus a business tool whereby the optimum group of designs can be determined for further analysis and decision.

The findings were that the hypothesis is valid. For AC and DC systems separate indicators which form part of the optimisation process are required.

CHAPTER 1

OPTIMISING THE LINE FUNCTION

1.1. INTRODUCTION

Overhead power lines are long mechanical structures with an electrical function linking substations together. Each line can be modelled as a single device in the power system to transmit power over long distances. These comprise many components such as conductors, towers, foundations and fittings. The combination of the various components, including the phase spacing, bundle configuration, number of sub-conductors in the bundle, and the templating or design temperature of the line together determine the values of electrical parameters resistance, inductance and capacitance (expressed as R, X and B when calculated using system frequency) that establish the power flow capability. They also affect the structure design, foundations, line costs and probable operating performance.

It is possible for the components to be optimised in isolation from each other, by engineers from different disciplines; conductors – electrical, towers – mechanical and foundations – civil. This thesis proposes a more integrated approach to line design to ensure the overall design is optimum in the context of the needs of the network

The combination of the various components include the phase spacing, bundle configuration, number of sub-conductors in the bundle, the templating or design temperature of the line and so on. The tower types and their suitability to the terrain need to be designed to ensure the overall design complements the decisions relating to conductor configuration.

It is thus possible to design a line with possibly 5 different tower families per line, approximately 10 conductor types, 5 to 6 phase configurations and 5 or 6 bundle configurations. This results in a large amount of different line designs utilising the different tower, conductor, phase and bundle configurations. The issue then becomes one of deciding which line configuration is to be used in the final design.

Line optimisation techniques are normally employed to optimise the tower type for a given bundle configuration or to optimise a particular tower top geometry for a particular phase spacing. According to literature research, covered in Chapter 2, few techniques employ an integrated approach whereby the entire line's function is met by various bundle, conductor, tower and foundation types.

Techniques have been developed by Stephen [2004], and Vajeth [2004] to objectively decide on the best group of line designs to develop further into detailed designs and finally construct. These generally involve a method whereby the designs can be used to score the design out of 10 [Stephen, 2004] or to represent the design options by means of a monetary value [Vajeth, 2004]. The present techniques have been exclusively used for AC lines and not DC.

The author of the thesis has been involved over the past 20 years in the field of line design and was the author of the papers referred to as [Stephen]. The original work in this thesis includes the developed of the original work as outlined in the work referenced by Stephen as well as the development of the HVDC indicators which has not been done before.

1.2. KEY ISSUES

The design of overhead lines (new lines, uprating or refurbishment) in the deregulated environment is critical to the competitiveness and profitability of the utility company. If, for example, the design limits the power transfer to levels that restrict ability to connect power generation, it can be financially onerous in terms of penalties [Tunstall, 2000]. In addition the limitations imposed on capital expenditure by finance directors setting budgets and approving projects, make the optimisation of line design a critical activity.

The design of lines has been practised with a few well-known standard towers, conductor and foundation combinations being used. In the literature study in Chapter 2 there are limited references employing checks as to whether these line designs optimally suit the intended function of the line as determined by the network planner. An indicator termed the “Appropriate Technology Indicator” or ATI has been developed and has been in use in Eskom, South Africa since 1992 and described by Stephen [2004]. This allows for many different design combinations to be investigated and objectively compared.

Planners in utilities may be provided with a number of standard design options such as towers and bundle designs from which to select, the planner will then decide from a very narrow group of solutions for the final solution to be implemented. This practice can be very costly as is shown in Chapter 5 where there are over 13 different line design options that will meet the planners requirements for load transfer. The final design may be more cost effective than the few standard designs offered.

Implementation of new tower designs is also possible especially with respect to long lines where the cost of developing a new tower may be warranted. The time taken for development and testing of a new tower design is easily accommodated in the long time taken to procure line routes. Thus the tower design activity is rarely on the critical path in a project.

This research intends to describe the different aspects of line design as well as to formulate and rigorously test the Appropriate Technology Index (ATI) and its components.

1.2.1 Line Design Versus Component Design

It is important to understand the difference between component design and line design. Component design refers to the design and optimisation of towers (covered in part by Pohlman [1991]), conductors (covered in part by Douglass [2004]) and hardware. Line design refers to the application of these components in the field and relates to the optimal position of structures and the selection of the best structure for the position from a suite or family of structures. This is covered in part by EPRI [1986].

In addition the line components and the application of the components need to ensure that the line is optimised for the intended purpose. This research intends to cover this aspect which is not covered in the mentioned references. This aspect is explored further by EPRI [2005].

The aim of this research is to devise a method whereby the line designs can be objectively prioritised, from a functional point of view. This means that the line design must meet the network requirements as specified by the planner.

The final solution may not be “optimum” in the mathematical sense, in this case it is the design that best fits the needs of the utility taking into account the present conditions and future load growth, load profiles and load under contingency and emergency conditions. The method proposed may not be able to determine the best option but allows for the utility to determine the best group of options from which a final decision based on the input from a number of stakeholders can be made. It may be found that the lowest initial capital cost is not necessarily the best option

1.3. GAPS IN CURRENT UNDERSTANDING

The main perceived gaps in the current practice and understanding of transmission line design are:

1. Designers do not include the planning input in an iterative process whereby the planner may alter his requirements to suit the network and line requirements.
2. Designers do not combine options to easily view the best family of options which can be further optimised or investigated.
3. Planners may not get feedback, after the event, regarding the validity of their estimates.

The research needs to further examine the manner to determine the set of options for the line from an integrated viewpoint ensuring that the end result gives the utility the best set of options to suit the lines intended function.

This process is not a simple one. Stephen [2004] alludes to the fact that there are over 100 variables involved in this process. This is considered to be understated as according to Stephen [1992], it can be seen that merely the determination of the thermal rating of a line involves over 100 variables. The full line optimisation involves over 1000 variables. It also involves variables that are difficult to quantify such as visual perception of tower types to homeowners which may determine one option over another.

The process commonly used worldwide (obtained from discussions with designers in Cigré), is to determine the power transfer capability required for the line. Once this is completed, a standard conductor type is chosen, this is normally achieved by planners who use standard configurations for load flow modelling. This applies to the conductor bundle as well. For example the standard bundle types may be quad Wolf 158mm^2 bundle or quad 429mm^2 bundle (Zebra conductor) (refer to Appendix 1 for conductor details). The planner will choose one or the other and request that this line be built.

The components such as towers, foundations, hardware and conductors are then generally optimised in isolation without altering the standard conductor bundle solution as proposed by the planner.

This research aims to provide methods to ensure that the final solution or group of possible solutions based on the function or purpose that the line is meant to perform (mainly expressed in terms of power flow and impedance) is the optimum. It is proposed to achieve this by suggesting an objective way to determine the most appropriate design options.

The ATI's developed for both AC and DC lines will enable the designers to determine the best set of line design options for further in depth analysis. It is not a tool that will, by multi-criteria analysis or other methods, determine the optimum line design for a particular function or purpose. It is therefore not an "objective" measure in the mathematical sense where a single solution can be found in all cases after detailed analysis, it is more a business tool which will enable designers to focus in on a set up line design options from which a final design can be selected for implementation.

The intent is to have simple indicators for which values can be easily determined from the analysis normally performed in the process of designing a line.

It is a comparative indicator and will indicate the best options from a group of design options considered. It will not indicate what designs have NOT been considered

The indicator also assumes that reliability, constructability, and maintenance factors have been taken into account with the proposed designs. It is for this reason that the indicators are not meant to determine the best line design without any further analysis being done. The indicators are there to indicate the best overall design options, which can be explored further taking all aspects, such as reliability, etc. into account. Note that the initial options must take standards into account, such as in IEC [IEC 60826, 2003] where wind loading is determined. The reliability considered in the final group of designs will be for the specific terrain, atmospheric conditions (for instance lightning and ice) and maintenance practices present in the geographical area for the line. These are detailed investigations for the specific line design.

The present day indicators described by Stephen [2004], are exclusively linked to AC voltages. It is necessary to expand the use of indicators to include DC as well. For example, the surge impedance loading which relates to the power transfer in AC is not relevant to DC. Other factors such as technical losses (losses as a result of conductor heating as opposed to non-technical losses which are a result of meter bypassing or human activity) may play a far larger part in DC line design as the lines are normally far longer than AC lines and carry a higher current density

1.4. HYPOTHESIS

It appears that one or a small set of appropriate technology indicators can be used by network planners and designers to identify the best group of overhead lines to meet specified objectives. These indicators can be used for a wide range of applications for AC and DC lines.

The thesis is directed to testing the validity of this hypothesis.

1.5. KEY RESEARCH QUESTIONS

To test the hypothesis the following key questions are to be answered:

1. How do planners specify their objectives for a proposed line?
2. What approaches are used elsewhere to "optimise" the power line planning and design, and how effective are those approaches?
3. What are the key parameters that need to be taken into account for determining the best group of designs for a particular function or purpose relating to AC lines?
4. What are the key parameters that need to be taken into account for determining the best group of designs for a particular function or purpose relating to DC lines?
5. How can these parameters be combined to form indicators for AC lines?
6. How can these parameters be combined to form indicators for DC lines?
7. What is the best method/process of objectively optimising lines?
8. What feedback can demonstrate the validity of the results of the combined indicator/s?

1.6. APPROACH TO BE TAKEN

The approach to be taken is therefore as follows:

1.6.1 Literature Review

To conduct an extensive literature review, searching for methods or practices that already exist and can be used for the purpose of objectively determining the optimum group of design options that will satisfy a particular line function or purpose.

1.6.2 Parameters Making Up The Line Function

To determine the parameters of the line that contribute to the function of the line, there needs to be a study undertaken for AC and DC lines of the nature of the parameters that make up the function of the line for AC and DC.

The parameters for AC could include the R, X and B parameters as well as the thermal requirements. For DC lines this may relate to the losses due to resistance and corona as well as the thermal power transfer requirements. These parameters may not be the only ones relevant to the optimisation of lines as others, such as reliability, constructability and wind loading for example, may be valid. The research process may indicate more needs to be taken into account. This is covered in Chapters 3 and 7.

1.6.3 Determination Of The Method To Optimise Line Design

The intention is to determine the most appropriate set of steps to optimise the design of AC and DC lines. These steps include obtaining information from the planners as well as developing the various line design options. The conductive (normally aluminium) material area required, conductor optimisation (type of conductor, structure), as well as tower and foundation types need to be determined, so that a group of designs that will meet the planner's requirements can be determined.

Thus the means by which the different parameters can be combined needs to be determined. This combination of parameters defines the best group of line designs that designers need to investigate further in order to finally decide on the solution to take through to the final design stage and implement.

This is to be done by investigating the previous research [Stephen, 2004] as a base from which to determine the most suitable method. This is covered in Chapter 4 (AC) and Chapter 8 (DC).

1.6.4 Determining The Best Group From a Set Of Solutions

It is then necessary to determine methods which will test whether the group of options chosen is in fact the best over the expected life of the asset. The term “best” in this context indicates a level of robustness that can cater for different loading conditions and maintenance costs. This is a difficult task as costs, such as maintenance on the line are often not captured making it difficult to identify the cost relating to the line or the particular design option. Initial thoughts are to investigate additional options in addition to the present standard options. These “non standard” options may otherwise not have been investigated.

The indicator proposed in this thesis hopes to provide a means whereby the benefit of changing to the new standard can be justified. Another method could be to investigate the optimisation that is likely to be done by utilities without such an index and compare with the optimisation possible with the index. This again is difficult as European utilities would not consider optimising a line as the opportunities and cost benefit rarely warrant it. As such NOK the Swiss utility has used the similar tower design for decades. Towers are not loaded to their maximum to allow upgrading.

Once the ratios (assuming ratios of parameters are the best solution) and the combination thereof are developed, it is necessary to find the optimum manner to determine the best group of options to investigate further. This can either be done for example, by a system of points (out of 10) or by measuring the financial savings in terms of reduced losses. This may prove to be the same for AC and DC. A combination of options expressed in financial terms and or points may be required.

This analysis is covered in Chapters 6 and 9

1.6.5 Application To Actual Case Studies.

Using the methods derived, the application of the method on actual case studies is then required to demonstrate the benefit of the method. It is intended to use actual lines designed in this manner since the indicator was introduced in Eskom as well as hypothetical designs in the case of HVDC. This will be covered in Chapters 6 and 9.

1.6.6 Testing The Hypothesis

The hypothesis, that the indicator does in fact aid optimisation of lines by readily identifying the best group of options and allows for a more effective line optimisation to be realised, then has to be tested. The method of testing at this stage is seen to be mainly subjective and involves studying the line design process, showing the benefit of the integrated approach using the indicator and thereafter indicating the benefit of the indicator in the optimisation process. This will be covered in Chapter 10.

1.7. SUMMARY OF CHAPTERS

The summary of the chapters is therefore:

Chapter 1 Optimising the line function – Introduction to the topic.

Chapter 2 Literature survey.

Chapter 3 AC parameters – Determination of parameters that determine the characteristics of the AC transmission line.

Chapter 4 Optimising AC line design – proposed methods to optimise the AC line design based on the parameters defined in chapter 3.

Chapter 5 Parameters required for objective determination of optimal line – Determination of parameters that can be used for the objective determination of the group of best design options.

Chapter 6 Indicator for objective determination – Development of an indicator that can assist in the objective determination of the group of best design options

(note that Chapters 3-6 deal with only AC transmission lines).

Chapter 7 DC parameters - Determination of parameters that determine the characteristics of the DC transmission line.

Chapter 8 Optimising HVDC line design - proposed methods to optimise the DC line design based on the parameters defined in chapter 7.

Chapter 9 Development of a HVDC line design indicator - Development of an indicator that can assist in the objective determination of the group of best design options for HVDC lines.

Chapter 10 Hypothesis testing – testing of the Hypothesis for AC and DC lines as well as possible suggestions for future work.

1.8 INTENDED SCOPE FOR USE OF THE INDICATORS

The design indicators are intended for use for the optimisation of line designs given a certain voltage and power flow. Thus the issue of different AC or DC design voltages, the number of circuits on a tower and the voltages thereof, multiphase options and low frequency transmission is assumed to be decided prior to the use of the indicators. The indicators can be used at all voltages but most of the applications are seen to be at voltages above 33kV. The reason being that at voltages of 33kV and below the limitation is mainly voltage drop rather than stability or thermal rating. In addition lines in this lower voltage range are normally designed based on standard design configurations. It is often not optimal to design a structure or select a specific conductor for a 33kV line as the capital cost of the line cannot accommodate the additional cost of tower development, conductor development or the additional items required to be placed in stores.

1.9 CONCLUSION

In testing the hypothesis, it is thus proposed to study the parameters for AC and DC lines. With the parameters known, it is intended to study means of optimising the AC and DC lines. From the parameters and optimisation methods it is proposed to develop indicators whereby the optimal group of designs can be identified for further analysis and implementation. The use of these indicators will then be tested on actual case studies from which the hypothesis can be tested.

CHAPTER 2

LITERATURE SURVEY

2.1. INTRODUCTION

In reviewing the literature it was considered pertinent to follow the questions posed in the previous chapter. In this manner, it is possible to determine which questions have been researched and answered via the literature.

2.2 SPECIFICATION OF PLANNING OBJECTIVES

The relationship between the planner and the design is described in a document prepared by Cigré JWG B2-C1 19 [Pramayon, 2010]. It describes the relationship in a generic fashion that is applicable whether or not the staff are in the same company or department

An Eskom internal research report [Stephen, 2005], suggests a method whereby the planners can describe their requirements in tabular form. This table provides a simple method to provide information to designers in order to optimise the line design to remove the network constraints as required by the planners. The parameters specified include the daily and annual load profiles as well as the impedance requirements of the line. The line reliability is also specified. The tabular format used is not critical to optimisation but allows for a standardised approach and is simple to apply.

The specified parameters assist the designers in determining, via an optimisation process, the templating temperature (which provides for the thermal rating required) as well as the line impedances which depend on the bundle and conductor configuration and provide for the correct impedance to be realised. (The templating temperature is not a key element in the optimisation process but is one element in the overall process in determining the overall conductor, tower and foundation combination.)

Certain text books deal with planning, but one [EPRI 2005, p 21] states that the results of overall planning include "conductors, voltage, shield wires, number of circuits". It does not deal with the objective of the line as determined by the planner.

2.3. KEY PARAMETERS FOR AC LINES

Key parameters in this thesis are those which define the function of the overhead power line (in this case for AC lines). The function of the line, that is to "transmit power over long distances" [Stephen, 2004, p1], is dependent on the impedance of the line defined by the R, X and B parameters.

Other constraints exist in the determining of the correct bundle and phasing configuration which will result in the required R, X and B being met. These are the corona constraints, electromagnetic fields, thermal limits and flashover probabilities. The latter affects the required reliability level from an electrical perspective.

The function of the line is defined by the network planners depending on the load and network configuration. In determining the R, X and B parameters the system losses are taken into account.

EPRI [2005] describes the calculation of the impedance parameters and the corona limits in great detail. The AC resistance is not covered in sufficient detail as it does not cover the transformer effect. This is covered in more detail by Morgan [1965] and Barret [1986] as well as by Douglass [2008]. Morgan [1965] described a series of equations based on certain experimental data for the determination of AC resistance. Barret [1986] derived equations relating to the AC resistance of the "Grackle" conductor with layers being removed to give AC resistance of single, double and triple layer conductors. Douglass [2008] combines the two theories expressed by the previous authors into a single model that can be programmed on Math Cad or similar programme.

The tower top geometry design, taking into account the likelihood of flashover and hence a component of reliability is covered by Ghannoumn [1995]. Tower top geometry relates to the position of the conductor bundle in tower window as well as the location of the other phases in relation to each other and the supporting structure. The flashover refers to the flashover between the conductor bundles and the supporting structure.

The sag is the distance between the conductor and an imaginary line drawn between the attachment points. The sag varies as a function of creep, loading from ice and wind as well as the temperature of the conductor due to current. The variation with sag and temperature is described in Douglass [2007] and shown in figure 2.1.

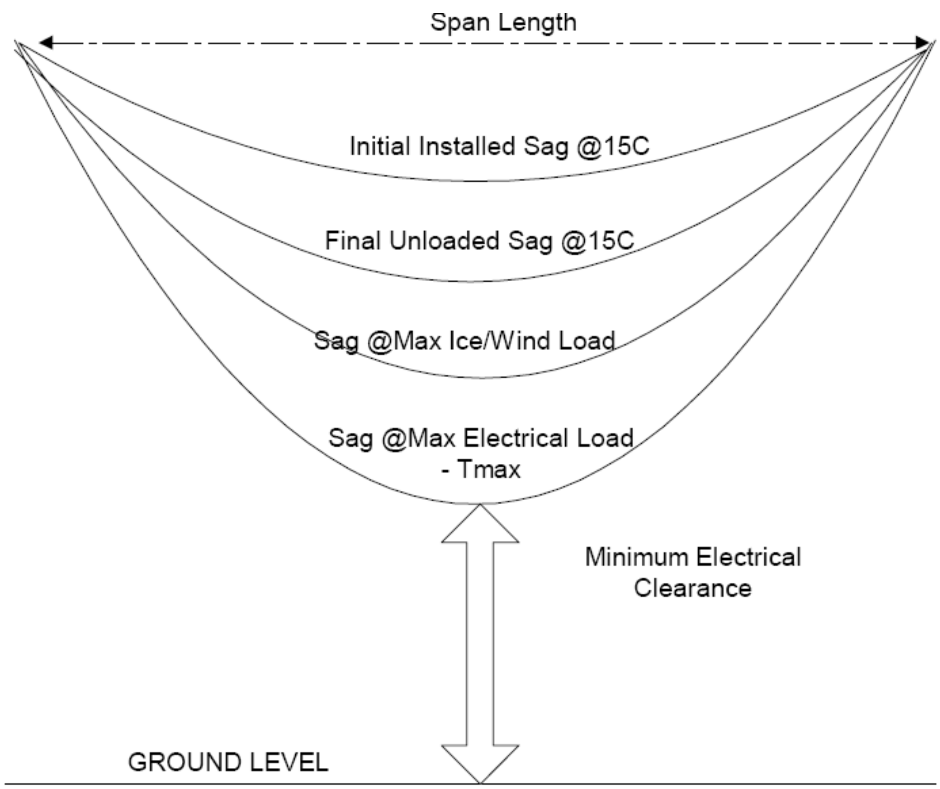


Figure 2.1 - Catenary variation with conductor temperature, ice & wind loads, and time after installation where Tmax is the maximum conductor temperature. [Douglass 2007]

Reliability is also covered by Muftic [2005] as well as in IEC [IEC 60826, 2003] although it refers mainly to mechanical reliability and not electrical reliability. This is the reliability of the line to withstand environmental pressures such as wind, ice and a combination of wind and ice.

Stephen [1994] describes an extension to the reliability based methodology by using statistical signatures of simulated probabilities of degrees to which certain line loadings are unsafe. These signatures can then be used to determine whether certain tower top geometries, templating temperatures and combination of templating temperatures and conductor types will result in a lower or higher reliability than another.

Thermal limits are covered by Stephen [1992], Swan [1995] and Stephen [1996]. Stephen [1992] describes the steady state equation to determine the conductor temperature for a given set of weather parameters. Swan [1995] proposes a method, whereby the thermal rating of a line can be referred to a particular risk of an unsafe condition arising. This method is later termed by Stephen [1996] as the “absolute” probabilistic method. Stephen [1996] is a guide describing different probabilistic methods and their application in determining the thermal rating of overhead AC lines.

In relation to uprating of lines from a thermal viewpoint, Kopsidas [2009-1, 2009-2, 2011] investigate increasing the thermal rating by changing conductor types (including high temperature conductors) and retensioning. Models to determine the rating of a line for a given OHL structure is also given. The work by Kopsidas [2009-1], investigates the performance of the line from a mechanical and electrical viewpoint by altering the conductor from ACSR to AAAC. This is also examined in Bell [1999] and Tunstall [2000] where the National Grid at the time had to increase ratings due to different power flows from Independent Power Producers. These papers deal with the parameter of thermal rating and the methods described are means to increase the thermal rating of the line. This is one aspect of the overall line optimisation. The research deals with the modelling and behaviour of high temperature conductors on 33kV lines and supports the findings of Douglass [2004] in selecting these conductors for special application to remove thermal constraints.

Other methods to increase the thermal rating of the line are described in terms of the dynamic rating of the line in Seppa, [2000], Roberts [2008], and Stephen [2000]. These are direct and indirect methods whereby the position of the conductor is determined by either calculation (indirect) or actual measurement (direct) the sag tension relationship of the actual conductor is determined from which the conductor rating in real time can be derived. An average increase of approximately 10% is possible using these systems. It should be noted that these systems are more related to the operation of the line and not the design of the line, however, the use of a dynamic system can be decided at the design stage. In the case of Roberts [2008] dynamic rating is used to delay system strengthening. In the design stage the use of dynamic rating can be considered if the line is thermally rather than voltage or stability limited. In this case the dynamic rating system can be used to increase the calculated steady state rating should ambient conditions allow it. This will be beneficial if for example the line has a winter peak with lower ambient temperatures and perhaps higher wind speeds.

The parameters can then be used to optimise the overall line design. Note that there are limited references (as shown in the previous section) that combine the parameters to determine the best line design. There are also limited references that indicate the effect of change from one parameter on another parameter. For example an expanded bundle will reduce the line impedance but may reduce the line to ground clearances and hence the thermal rating. It may also adversely affect the reliability due to reduction in clearances in the tower top. Audible noise due to corona also needs to be considered as this expanded bundle could worsen this parameter. These interactions do not seem to be covered in literature.

2.4 KEY PARAMETERS FOR DC LINES

These parameters are mainly covered in EPRI [1994], the environmental impacts are discussed in Koscheev [2003]. This includes resistance (R), DC corona, field calculations (V/m) and insulation strength requirements. Koscheev [2003] mentions that the environmental constraints relating to DC lines are similar to AC lines.

With regard to resistance, Stephen [1992] describes a simplified formula to calculate the DC resistance of a conductor. This takes into account the lay length, number of layers and strands. Resistance in DC lines is an important parameter due to the high cost of losses due to resistance [Nolasco, 2009]

The DC parameters are on the whole, less complicated than that of AC. This is due to the lack of varying electric and magnetic fields as well as issues such as capacitance to ground and transformer effects in conductors. Thus there are no inductance (X) and capacitance (suseptance) (B) parameters. In AC systems these form part of the surge impedance loading which is important in the determination of the conductor bundle and phase spacing.

The works by Maruvada [1970 and 2000] discuss the determination and evaluation of corona in DC lines. This is an important parameter as it determines the bundle size and spacing between poles.

The EPRI works [1993, 1994], cover the basic design parameters for the HVDC line design which includes tower configurations, corona, voltage calculations, electric field calculations, insulation etc.

The characteristics of HVDC lines as well as the choice of voltage for a specific line length and power flow requirement can be found in the Cigré brochure [Nolasco, 2009]. This document covers line costs as a function of corona (E_{crit}) and the cost of the line as a function of conductor aluminium size. This is extremely useful in determining how to combine this information into an indicator that can be used by designers to readily determine the appropriate group of line designs.

A critique of the work of Nolasco [2009] is that it is limited in the type of tower used. In this case a simple self supporting bipolar tower. The reason for this could have been the extra amount of permutations for analysis would have made the document unwieldy and too large. Another criticism is the lack of conductor types and large number of sub-conductors in the bundle. Analysis in Chapter 7 indicates that a large number of sub-conductors in the bundle would have been more beneficial to the design than the conductors chosen for analysis.

The use of DC lines is mainly a point to point application and the lines are longer than AC lines in general. Thus aspects such as losses, which are dependent on R, play a large part in conductor optimisation. This depends on the conductor type as well as the voltage used. This is covered in Singh [2005].

These references refer to the combination of parameters in AC lines. No references of a similar nature was found for DC lines although the Cigré work [Nolasco, 2009] combined all DC parameters of the terminal equipment and line design to determine the best overall set of options to pursue.

2.5 COMBINATION OF PARAMETERS

The electrical parameters are covered in EPRI reports [2005 and 1986] which deal with the corona, power transfer, flashover criteria etc. There is no link between the electrical parameters and the mechanical parameters such as the increased wind loading as a result of having more sub conductor bundles per phase. More sub conductors in the bundle will improve the corona performance.

The mechanical parameters are covered in IEC, [IEC 60826, 2003] as well as in Ghannoumn [2001] and Pohlman [1991]. This again deals with the determination of the mechanical loading on the tower with different wind, ice and combined wind and ice conditions. There is no relation as to how the electrical parameters will be affected by certain mechanical configurations. For example the mechanical loads in the tower leg of a guyed vee tower will be lower if the guy angle is increased. However, the increasing of the guy angle will reduce the distance between the guy wire and the phase conductor. This will reduce the reliability of the line. This is what is meant by combining mechanical and electrical issues. The only reference that combines some mechanical and electrical parameters is Ghannoumn [1995]. The interaction between electrical, mechanical and civil parameters is covered in Stephen [2005]. The link between these parameters and the planning requirements is covered by Stephen [2004], and Vajeth [2004].

2.6 METHOD TO OBJECTIVELY OPTIMISE OVERHEAD LINES

The basic concept of this research is to determine a method whereby the line can be optimised in an objective manner. This optimisation refers to the function of the line which is to transmit power over long distances.

Optimisation by Peyrot [1992] and EPRI [1986], for example, refer to the optimisation of line components assuming the conductor is known. EPRI, [1986] describes optimisation of lines relating to line route and profile. This optimisation is performed using programmes such as TLOP [Peyrot, 1992] and more recently PLSCADD [Powerline, 2010], which uses cost as the optimising measure and is therefore objective. The issue is that it does not address the matter of whether the line design meets the criteria of the planner or the network.

Component optimisation can be confused with line optimisation. It is thus important to understand the difference between component design and line design. Component design refers to the design and optimisation of towers (covered in part by Pohlman [1991]), and conductors (covered in part by Douglass [2004]). Line design refers to the application of these components in the field and relate to the optimal position of structures and the selection of the best structure for the position from a suite or family of structures. This is covered in part by EPRI [1986].

EPRI [2005] deals with the planning output which is then entered into the line design process in series with no feedback loops back to the planning process, which is necessary to determine if the option is indeed optimum from a network point of view. It is important to note that the planning input is an integral part of the line design process. A serial process with no feedback to the planner is unlikely to meet the planner's requirements in the solution of the particular network constraint.

In addition the line components and the application of the components need to ensure that the line is optimised for the intended purpose. This research intends to cover this aspect which is not covered in the mentioned references. This aspect is explored further by EPRI [2005].

Many other authors, including Paris, [1992], and Pohlman [1991] deal with the variations in towers, the cost components of lines and provide methods to determine component costs for different line and component designs.

Cluts [1991-1], Douglass, [1990], and Cigré WG09 [Cluts, 1991-2] are very useful in determining the relationship between components and costs. This is useful in understanding the cost elements of lines and identifying areas to reduce costs. It does not deal with the overall optimisation of the line costs but will assist in estimating costs and quickly comparing different design options.

Hickey [1992] deals in part with the environmental aspects of line design and construction. There is extensive inhibiting legislation relating to transmission line routing. Hickey [1992], states that the cost of the Right of Way (ROW) is such that it may overshadow the cost of the line. In this case the cost of the ROW should form part of the line cost and the total cost of both the line and the ROW should be optimised to determine the best line design and ROW options. For example a narrow based tower may be more expensive than a wider guyed tower but the servitude (ROW) cost may result in a total cost of the line and ROW with the guyed tower being more than that of the narrow based tower and the narrower ROW.

The probabilistic analysis, as shown by Douglass [2004], Ghannoumn [2001], and Cibulka [1992] which deal with the reliability of lines or the risk of certain load levels to the public based on weather conditions can be used as a subset of the iterative process.

Other authors such as Nashid [1992], and Stephen [1992], McMahon [1996], deal with the techniques to solve specific line design problems such as increasing the thermal rating or current carrying capacity of a line by selecting the optimum conductor for the particular line concerned.

Grant [1987], Douglass [1988] and Kiessling [2002] approach optimisation from a perspective that is wider than the previous references. They include the component optimisation as well as the line design optimisation in the total ambit of optimisation. They do not, however, include a link back to planners to check the functionality of the design relating to the requirements. They also do not include an iterative process whereby the planner would alter requirements to obtain the best design from a network and component perspective.

Baldick [2009] covers methods of uprating lines in view of the current situation in most countries where additional line routes are extremely difficult to procure. This paper covers the various line design options and includes other devices such as FACTS and series capacitors which can increase the power flow down a particular line. Costs are determined for the different uprating options and provided in a table at the end of the paper. Although this paper does not cover all parameters into one indicator, it is one of the few papers referenced that consider a wide range of line design items (including new conductor designs).

Mc Mahon [1996] deals with the comparison of overhead lines and cables. It does not, however, deal specifically with costs but more with ratios. This is useful in determining the optimum device for transmitting power over long distances as cables may limit environmental mitigation costs. At present, the cost of cables at voltages above 132kV are still too high in most countries for general use instead of an overhead transmission line. This trend is changing, with the environmental constraints imposed on overhead lines.

Muftic [2005] covers such items as the optimisation of conductor, ground wire and line design but does not reference this back to the requirements of the planners. The optimisation of the conductor encompasses a large number of parameters, such as bundle configuration and corona limitations.

Vajeth [2004] refers to a method whereby the different conductor and tower options can be ranked. It (i.e. the method) is similar in concept to that described by Stephen [2004], however it uses actual costs (life cycle cost (LCC)) instead of an index based on points out of 10.

Stephen [2004] uses an objective Matrix method whereby the different parameters are combined and scored out of 10. The present practice is given a score of 3/10 and a linear interpolation is determined based on the 10/10 target. The measure is a comparative measure and not absolute. It is also a simple, easy to calculate measure. This is work of the author based on developments in the early 1990's. The work only applies to AC designs and not DC.

Bekker [2006] introduces a different approach to evaluating different options using the Shackle model. This needs to be pursued further but may be more suited to less certain environments than that of overhead line design where component behaviour is well documented. The Shackle model may be of use in scenario planning for load forecasting relating to the line. With the scope of the use of the indicator as defined in section 1.8, there is a fair degree of certainty. In addition the indicator proposed is an engineering tool to enable the designers to objectively decide on the set of design options to take further. Thus the use of models described by Bekker [2006] is not really appropriate here.

Mavrotas [2003] describes a method whereby wind generators can be selected based on available capacity for absorption in the network. This uses the ELECTRE-TRI methodology to determine the categories and attributes of the tendered generators. It then uses a multi parameter linear programme to determine the best group of options in relation to the generators to choose. The ELECTRE-TRI is useful to place options into categories which may be applied to different categories of line design for a particular application. The method is perhaps useful only in the initial stages of line design where DC or AC may still be an option for example. Matsatsinis [2005] proposes a similar method whereby weightings can be determined for different attributes using different Decision Makers (DM). This situation is valid for the decision on certain Transmission lines where DM's must decide whether the Surge impedance loading (SIL) or thermal rating for example is the more important.

Further enhancement to the analysis of the alternate designs taken the uncertainty of the input data into account is described in Hyde [2003] where uncertainty in the preference ranking organisation method of enrichment evaluation (PROMETHEE) MCDA Method. Planners' input is often stochastic in nature. This method may assist in determining the most robust design. Stephen [2004] uses the ranking method to determine the best design. In short the design with the highest ranking on average across all weighting options was chosen or recommended. The method described in Hyde [2003] may enhance this approach.

Scott [2005] refers to the use of MCDA for deciding on different projects relating to integrated development plans (IDP) for use in Municipalities. This uses a weighting factor and subjective scoring. This method is too broad for the deciding on different line design options which must result in a more objective method.

Pictet [2005] describes a method whereby decisions can be made without discussion which could be useful in deciding which line option is to be finally decided on. A combination of methods of Stephen [Stephen 2004] and MCDA may be of use.

Mustajoki [2005] describes Multi-attribute Value Theory "in which the overall values of the alternatives are composed of the ratings of the alternatives with respect to each attribute". This is an interesting alternative to complement the index proposed by Stephen [2004].

Seppala [2002] describes a method very similar to the "Objective Matrix method", described in Stephen [2004], the matrix method is a way of quickly analysing attributes of different units.

2.7 BENEFITS OF USING THE OPTIMISATION TOOL AND PROCESS

The benefits of using an optimisation process have been stated by Stephen [2004] and Vajeth [2004]. In the case of Vajeth [2004] the benefits are stated in monetary terms. In the case of Stephen [Stephen 2004] the benefits are less evident and one can either use the life cycle cost (LCC) estimate or the initial cost estimate for an estimate of the monetary benefits between the options. In an internal Eskom design report [Tap Engineering, 2007] the benefits are further developed depending on the cost of capital.

2.8 CONCLUSION

The references studied indicate that although there is a large amount of papers on specific elements or components of transmission lines and their behaviour, there is a limited amount of literature on the topic of objectively determining overhead line design especially with reference to the planning requirements.

Thus, the questions asked in the previous chapter have not all being answered by the literature. Main questions unanswered are questions 1, 5, 6, 7 and 8 which include the planners requirements, the methods to combine the parameters for an indicator in AC and DC cases and the process to optimise the line design. Although Stephen [2004] and Vajeth [2004] cover the AC aspects in answer to the questions, they do not cover the DC aspects.

Articles by Kopsidas [2009-1] and Seppa [2000] cover aspects such as further research into high temperature low sag conductors and dynamic rating of lines respectively. The use of HTLS conductors is also covered in Tunstall [2000] where a practical application for the use of the conductor in the then National Grid is given.

The papers reviewed in the literature survey were selected specifically dealing with overall line design optimisation and hence did not cover the broader aspects of line design such as tower top geometry, foundation design, conductor design etc. The scope of the thesis deals with the methods to combine the aspects of line design to determine the optimum range of designs that will meet a specific pre-determined function of the line. This involves all the components of the line and their relation to parameters that define the function such as thermal rating, life cycle cost etc.

CHAPTER 3

AC PARAMETERS

3.1. INTRODUCTION

The power line is a device that transmits power over long distances, in this respect it is different in nature to other devices such as transformers in that the design of the line is dependent on terrain and ambient conditions to a far greater extent. The benefit of this for the utility is that the line can be specifically designed for the position in the grid to a far greater extent than other devices. The line can be designed to suit the particular power transfer and impedance characteristics and optimised for a particular terrain and set of ambient conditions.

This chapter investigates the parameters that determine how the line will function in the network. The aim is to determine the set of parameters that can eventually be used in the objective indicator in the optimisation process.

3.2. LOAD FLOW CHARACTERISTICS

The surge impedance of the transmission line is defined as the [Muftic, year] square root of the ratio of the line inductance to the line capacitance.

Thus $$Z_S = \sqrt{\frac{L}{C}}\Omega \qquad [3.1]$$

Where Z_s is the surge impedance

L is the series inductance and

C is the shunt capacitance.

The Surge impedance loading (SIL) is the load at which the inductance and capacitance will negate each other and represents an indication of the capability of the power line to transfer load.

$$SIL = \frac{(V_{LL})^2}{Z_S} \qquad [3.2]$$

where V_{LL} is the line voltage.

It is desirable in most cases to increase the capability of the line to transfer load thus to increase C and reduce L to maximise this parameter.

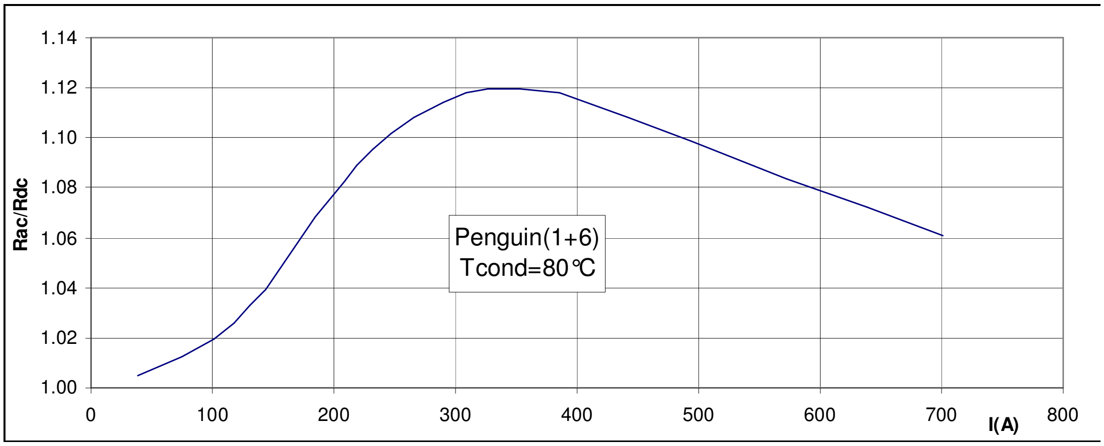
It is important to understand the parameters that make up the Resistance (R), Inductance (L) and the Capacitance (C) of a transmission line. Note that the L is calculated as impedance X and C is the suseptance B in the modelling of the line thus R, X and B have an effect on the load flow. X and B are functions of the frequency of the AC voltage.

3.3. CALCULATION OF AC RESISTANCE.

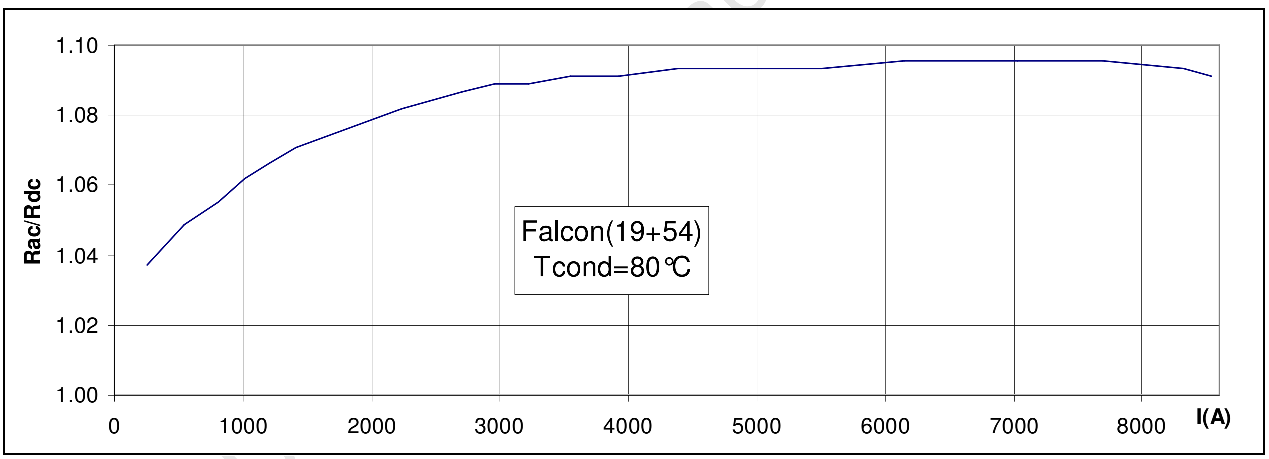
The AC resistance of a transmission line is described in detail in Douglass [2008]. For this thesis, it is important to understand the main components that affect the resistance of AC lines.

3.3.1 Construction of The Conductor.

The AC resistance is dependent on the construction of the conductor in terms of the material used (aluminium, alloy, steel, and the combination of these). The stranding of the conductor also has an effect on the AC resistance, as the lay ratio in each layer will affect the current flowing in that layer as well as the impedance of that layer especially in steel cored conductors. It was shown [Douglass, 2008] that the transformer effect could be negated by varying the lay ratio of the each layer of the conductor so that the effect of the current spiralling around the steel core could be reduced. Temperature has an effect on resistance with the higher the temperature the higher the resistance [Stephen, 1992]. The AC resistance is a function of current magnitude with the higher the current the higher the resistance [Douglass, 2008]. In aluminium conductor steel reinforced (ACSR) conductors the single layer conductor is more susceptible to resistance increase with current than double layer. In the case of the triple layer it is more affected than double layer. This is because the current spiralling in different directions for each layer tends to cancel the effects of the eddy currents created in the core. AC resistance is also a function of frequency with the higher the frequency the higher the resistance.



Graph 3.1 AC to DC resistance ratio of a single layer ASCR conductor (107mm^2) as a function of current [Douglass, 2008]



Graph 3.2 AC to DC resistance ratio of a 3 layer ACSR conductor (800mm^2) as a function of current. [Douglass, 2008]

From graphs 3.1 and 3.2, it can be seen that the single layer conductor can have an AC to DC resistance ratio of 1.12 for currents in the order of 370 A. This is around 4 A/mm^2 and is above the economic limit of a line normally considered to be around 0.8 to 1 A/mm^2. However in emergency conditions it is likely that this level of current density can be attained. For the 3 layer conductor the effect is less with a ratio of 1.09 for the current density of 4 A/mm^2.

For reduction in AC resistance as a function of current, the ACSR conductors could be replaced with AAAC (aluminium alloy) conductors which will not display an increase in resistance as a function of current. However, the cost or availability may not suit the use of AAAC. In these cases if single layer is the optimum size to use the effect of AC resistance on current needs to be taken into account with load flows and conductor temperature calculations

3.3.2 Calculation of Inductance.

The inductance is a function of the Geometric mean radius (GMR) and the Geometric mean distance (GMD) of bundle and phase geometry.

$$GMR = \sqrt[n]{n \times r \times R^{n-1}}\, m \qquad [3.3]$$

Where

r = 0.7788 x radius of the conductor in m

R = Radius of the conductor bundle

n = number of sub-conductors

GMR = Geometric mean Radius.

$$GMD = \sqrt[3]{(d_{12} \times d_{13} \times d_{23})}\, m \qquad [3.4]$$

Where

d_{12} d_{13} and d_{23} are the distances between the phases.

$$L = 2 \times 10^{-7} \times l \times \ln(\frac{GMD}{GMR}) H \qquad [3.5]$$

L=inductance of the line in Henry's per length l in meters.

Thus to decrease the inductance which will reduce losses and enable higher power transfer, the GMR should be large and the GMD should be small. Thus the bundle size should be large and the phase spacing should be small.

3.3.3 Determination Of C

With reference to Muftic [year], the shunt capacitance of a power line is affected by the earth plane which affects the field of the charged conductors.

Line voltages, are a function of the line charges. In steady state AC conditions the relationship is given by Muftic [2005]:-

$$[V_i] = [P_{ij}] \times [Q_i] \qquad [3.6]$$

where

Q_i= charge on the conductor per unit length and

P_{ij}= are dependent on the geometry of the line as per equations below.

$$P'_{ij} = \frac{1}{2\pi\varepsilon_0} \times \ln(D'_{ij} / D_{ij}) \text{ m/Farad} \qquad [3.7]$$

$$P_{ii} = \frac{1}{2\pi\varepsilon_0} \times \ln(2h_i / r_i) \text{ m/Farad} \qquad [3.8]$$

where

D'_{ij} = distance between conductor i and image conductor j' in (m)

D_{ij} = distance between conductors i and j, in (m)

ε_0 = permittivity of free space (Farads/m)

h_i = average height of conductors (m)

r_i =radius of each conductor (m)

In simple notation

$$[V] = [P] X [Q] \quad [3.9]$$

To determine the currents in terms of voltages the following matrix form relations hold:

$$[I] = j\omega X[P]^{-1}X [V] = j\omega X[C]X[V] \quad [3.10]$$

where [C] is the capacitance matrix.

Thus for C to be high, which is the intent if the aim is to increase the line SIL, then [P] needs to be small. Thus D_{ij} needs to be small. This implies that the phases need to be closer together to increase the C value. Similarly the conductors need to be close to the ground to increase the C value.

3.3.4 Line Model

The parameters of a line are equally distributed over the line. The accurate model of the line is determined from differential equations from which the current and voltage can be calculated in matrix form by means of constants as follows:

$$\begin{bmatrix} V_s \\ I_s \end{bmatrix} = \begin{bmatrix} AB \\ CD \end{bmatrix} \times \begin{bmatrix} V_r \\ I_r \end{bmatrix} \qquad [3.11]$$

where ABCD are constants which can be determined from the following equations:

$$A = \cosh(\gamma \times s) \qquad [3.12]$$

$$B = Z_c \times \sinh(\gamma \times s) \qquad [3.13]$$

$$C = \frac{1}{Z_c} X \sinh(\gamma \times s) \qquad [3.14]$$

$$D = A \qquad [3.15]$$

where

$Z_c = \sqrt{\frac{z}{y}}$ = surge impedance in Ω [3.16]

z = series impedance /unit length (Ω/m)

y = series admittance / unit length (S/m)

$\gamma = \sqrt{zy}$ = propagation constant in per m. [3.17]

These equations can be simplified into lumped parameters for short (<100km) and very long (>200km) lines.

3.3.5 Summary

In summary, the SIL of a line can be altered by varying the bundle size and the phase spacing as well as the number of sub-conductors in a bundle. The resistance of the line can be altered by the type of the conductor chosen as far as lay ratio and composition of the conductor is concerned. Homogenous conductors, or non-steel cored conductors will not exhibit a variation of resistance as a function of current as will steel cored conductors.

3.4. CORONA LIMITATIONS

The following factors affect the corona on a conductor surface [Muftic, 2005, ch 6 p 133]

- System voltage
- Conductor diameter
- Clearances between conductor and adjacent phase conductors
- Clearance between conductor and earth
- Number of conductors per phase
- Bundle geometry (diameter of bundle position of sub-conductors)
- Conductor surface condition
- Atmospheric and weather conditions
- System frequency.

As Conductor diameter increases the surface field gradient decreases, however, when the conductor surface field gradient exceeds the inception voltage the radio interference and audible noise levels will be higher than that of a smaller conductor diameter with the same surface field gradient. According to Muftic [2005], this phenomenon is caused by the fact that the rate of reduction of electric field with lateral movement away from the conductor decreases as the conductor diameter increases. As phase to ground and phase to phase clearances increase the surface field gradient decreases in a complex way.

There are two relationships that need to be understood with regard to corona, the first is the corona inception voltage and the second is the surface field gradient present on the conductor. The corona inception voltage is that voltage above which the conductor will enter into visible corona. It is defined by Peek's law [Peek, 1911] as:-

$$E_c = 21m\delta\left[1+\frac{0.308}{\sqrt{r\delta}}\right] \text{ kVrms/cm} \qquad [3.18]$$

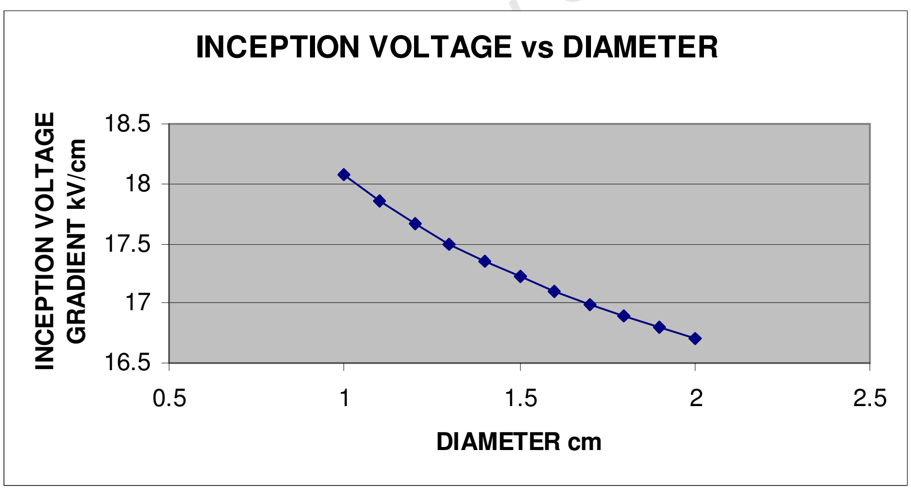
where

m = surface roughness factor which normally lies between 0.7 and 0.9 for a stranded conductor with an ideal smooth conductor being 1.

r = radius of conductor in cm

δ=relative air density

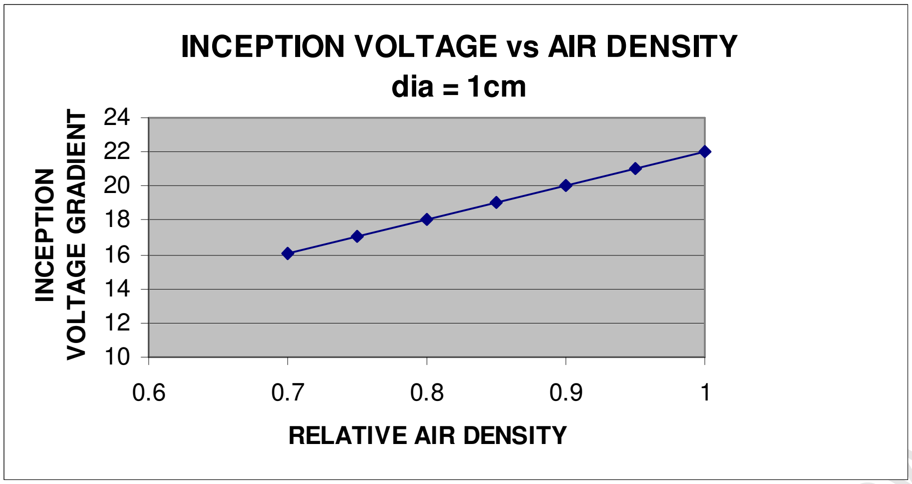
The higher the value of E_c the less chance of the conductor going into corona. The smaller the conductor diameter the higher the E_c. Thus the higher the gradient needs to be on the conductor before it will go into corona. This is shown in the following graph:



Graph 3.3. Inception voltage gradient vs conductor diameter.

Decreased air pressure also decreases the inception voltage gradient. Thus design of lines at high altitude (above 1000m) needs to be more cognisant of corona.

The effect of the air pressure is quite marked as shown in the following graph:



Graph 3.4 Inception voltage gradient vs Air density

The corona inception voltage is not dependent on the number of conductors in the bundle and is calculated as if it is a single conductor irrespective of the bundle configuration [Muftic, 2005]. This, however, is not strictly correct as the corona inception voltage is also a function of the number of sub-conductors. This is described in [Maruvada, 2011 sec2.8 p69], where it states that "Computational techniques are available to determine the field distribution in some cases, such as near a stranded conductor." This implies that the corona onset gradient is a function of the field distribution around the conductor which is a function of the other conductors in the bundle. This is not simple to determine and empirical evaluation is necessary in some cases.

The second aspect that needs to be taken into account is the calculation of surface field gradients. The design of the line needs to ensure that the ratio of the surface field gradient to the corona inception voltage is <0.95 [Muftic, 2005]

In order to calculate the surface field gradients on multiphase bundle conductors the following equations apply [Muftic, 2005].

$$[V]=[P][Q] \qquad [3.19]$$

where [V] and [P] are column vectors of the voltage and phase conductor bundle charges.

Thus $[Q]=[P]^{-1}[V]$ [3.20]

The average conductor surface field gradient is described as follows:-

$$E_{ave} = \frac{Q}{2\pi\varepsilon_0 nr} \qquad [3.21]$$

where Q is the total charge on the bundle, n is the number of sub-conductors in a bundle, and r is the radius of the conductor in cm.

The maximum conductor surface field gradient E_{max} is given by

$$E_{\max} = E_{ave}\left[1+\frac{(n-1)r}{R}\right] \qquad [3.22]$$

where R is the bundle radius in cm.

the elements of [P] are given by

$$P_{ii} = \frac{1}{2\pi\varepsilon_0 r}\ln\frac{2h_i}{GMR} \qquad [3.23]$$

$$P_{ij} = \frac{1}{2\pi\varepsilon_0}\ln\frac{D_{ij}}{d_{ij}} \qquad [3.24]$$

where D_{ij} is the distance between the first conductor (or bundle) and the image of the second, and d_{ij} the distance between the first and second conductors (or bundles - this is the phase spacing). The symbol h_i is the mean height of a given conductor phase bundle above earth.

In order to reduce the surface field gradient of the conductor in the bundle it is necessary to increase the number of conductors in the bundle thus reducing the E_{ave} and increasing the bundle radius to reduce E_{max}.

The factor Q is dependent on $[P]^{-1}$ thus the bundle radius and number of sub-conductors need to be increased in order to increase the GMR for component P_{ii}. The phase spacing d_{ij} needs to be increased for component P_{ij}.

The larger the conductor radius, the higher the corona inception voltage. The increase in sub-conductors in the bundle as well as the higher phase spacing have a larger effect on the corona inception voltage than that of the conductor diameter.

3.4.1 Design Limits For Corona

The minimum ratio for allowable corona performance according to [Muftic, 2005] is $E_{max}/E_c<0.95$ irrespective of the altitude. Thus the maximum expected surface field gradient should be less than 95% of the inception gradient. This provides for a margin of error or small irregularities to exist on the conductor without the conductor going into corona.

The audible noise limits that are recommended for outdoors according to SABS 60103 [1993] are as follow:-

Type of district	Daytime dBA	Evenings, weekends dBA	Night-time dBA
Rural	45	40	35
Suburban	50	45	40
Urban	55	50	45
Industrial	70	65	60

Table 3.1 Sound levels recommended for outdoors in South Africa [SABS 60103, 1993]

The important factor to realise is that, depending on the background level of noise, the disturbing noise level which is defined as 7dB above background noise may be exceeded.

Achievement of the limit of the audible noise level is difficult to achieve if the line's loading requirements are low relative to the system voltage as the aluminium area required is far smaller than the minimum area required taking into account corona design parameters. This normally leads to different alternatives being considered such as smaller conductors but more sub-conductors in a bundle. Practical considerations need to be taken into account such as stringing of large bundles of small diameter conductors is problematic. Small conductors also tend to move more erratically in the wind which could cause problems such as described in Chapter 5.

3.4.2 Rectification Of Corona Problems

Corona mitigation after the line is built is one of the most difficult aspects to rectify. This is because it requires either a reduction in system voltage (thereby reducing the surface field gradient) or the use of an additional sub-conductor which may not be possible without strengthening of the towers. Thus it is critical to ensure that the bundle design caters for all weather and construction possibilities to ensure that the audible noise limits are not exceeded.

3.4.3 Summary

The surface field gradient increases with smaller phase spacing and larger bundle size. It reduces with wider phase spacing and increase in the number of sub-conductors.

3.5. MECHANICAL CONSIDERATIONS

The detailed mechanical calculations will not be covered here, however, it is important to note that the design of a transmission line is often more cost effective when the loading on the towers is minimised allowing for smaller and less expensive support structures.

The main purpose of the mechanical system is to support the current carrying component. It is also important to consider all mechanical aspects of the line including the steel support in the conductors. Therefore if the mechanical aspect of the conductors can perform the dual purpose of carrying current and supporting load the more efficient the conductor.

The line is exposed to ambient conditions such as wind and ice loading which implies that the conductor system needs to be designed so as to minimise the effect of the wind and ice on the system. This is generally achieved by using fewer conductors in the bundle so as to minimise the wind load on the conductors. In addition, the lower the steel content the lower the ultimate tensile strength (UTS) of the conductors and hence lower loads result in the strain towers allowing for lighter tower designs. The same applies to ice loading with fewer conductors in the phase bundle the lower the overall ice load.

In certain circumstances with guyed and cross rope suspension towers, the wider the tower the lower the loads in the masts and the guys. Wider servitudes are therefore generally preferred if guyed structures are to be used. Guyed structures are generally lighter and hence less expensive than self-supporting structures.

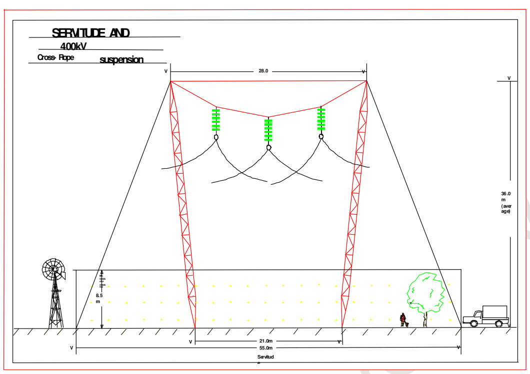


Figure 3.1 Cross Rope Suspension Tower (Variable Phase Spacing).

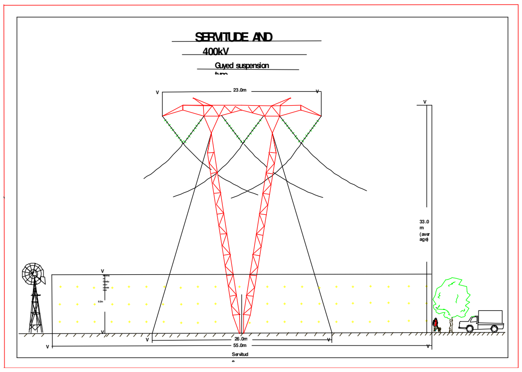


Figure 3.2 Guyed Vee Tower (Type 518).

Figure 3.1 and Figure 3.2 show the cross rope and guyed V tower designs. These tower types use guyed wires as supports as opposed to self-supporting towers which use lattice leg supports and no guy wires.

3.5.1 Summary

The fewer sub-conductors per phase, the lower the UTS and the wider the guy wires the more cost effective the line design from a mechanical viewpoint. This is especially true for guyed vee and cross rope suspension towers.

3.6. THERMAL RATING

The amount of current that can be transferred down an overhead line depends on the stability of the network as well as the temperature the conductor reaches. The limit is mainly to minimise the risk of safety to the public (as the conductor sags when heated) or to prevent strength loss in the conductor. According to Stephen [1992], the thermal rating of a line is termed "ampacity" and is defined as,

"The ampacity of a conductor is that current which will meet the design, security and safety criteria of a particular line on which the conductor is used."

The temperature or thermal component is encompassed in the term "design" in the above definition as the design of a line involves determining the templating or design temperature of the line which is the temperature at which the conductor is at the minimum height allowed in terms of law [Stephen, 1992].

The rating on the conductor is determined in the steady state (no energy stored in the conductor) equation and the dynamic equation (conductor is heating up or cooling down). The steady state of the conductor is determined by using the heat balance equation.

HEAT GAIN = HEAT LOSS

$$P_j + P_M + P_S + P_i = P_c + P_r + P_w \qquad [3.25]$$

where

P_j = joule heating

P_M = magnetic heating

P_S = solar heating

P_i = corona heating

P_c = convective cooling

P_r = radiative cooling

P_w = evaporative cooling

According to Stephen [1992], the corona heating is prevalent at times of high humidity and high wind speeds. It is thus normally irrelevant in the determination of the conductor temperature as the cooling effect due to the wind is far more dominant is greater than the effect of heating of corona.

Kopsidas [2009-1] refers to the ASTM code in relation to thermal evaluation or ampacity calculation. This is using the deterministic approach following the IEEE standard methods which involve a more empirical approach as opposed to Morgan which uses derived equations.

Evaporative cooling, on the other hand is extremely effective and can have a major effect on the temperature of a conductor. However, as the equation is used to determine the rating of lines for use in planning and operations, this cooling is ignored as it is rare that the entire line will be wet. To take it into account will result in ratings that are higher than could safely be used.

The P_j and P_M are incorporated in the AC resistance calculations which are covered in detail by Douglass [Douglass 2008], and by Stephen [1992] a simplified formula was used to determine the magnetic heating component. The transformer effect, covered by Douglass [2008] was not incorporated by Stephen [1992].

In short, the steady state equation is used for development of rating of conductors (normally deterministic). This rating is used by planning and operations staff to determine when network strengthening is required. operations staff use these ratings to determine when to load shed or transfer load. In the case of operations, these may be short term or long term ratings (Stephen 1992). It is possible to increase the load in the short term (30 minutes) above the steady state rating thus avoiding the shedding of load.

The ratings can be either deterministic or probabilistic [Stephen, 1992], [Stephen, 1996]. Deterministic "determines" the weather parameters up front and uses equation [3.25] to determine the current for a given conductor temperature. Probabilistic ratings [Stephen, 1996] take into account the risk to equipment and public for different current levels in different climatic areas. This can either be a relative risk ("exceedence level") or absolute risk. The latter can be used to compare the risk of an unsafe condition occurring to the risk of failure of other facilities such as failure in a nuclear station or earthquake etc.

One of the parameters that affect the thermal rating of transmission lines are the height of the conductor above the ground. The height affects the temperature at which the conductor can operate prior to an unsafe condition arising. Another parameter is the ability of the conductor to withstand the temperature at which the rating is determined. The increase in the current rating from 50ºC to 80ºC is shown in the table below [Eskom, 2000]

Conductor type	Templating temperature (deg C)	Rating (amps)
Wolf	50	354
Wolf	60	435
Wolf	70	492
Wolf	80	540

Table 3.2 Conductor Rating as a Function of Templating Temperature (height above ground) for 158-A1/S1A 30/7"wolf" conductor [Eskom, 2000]

The ability of the conductor to withstand the required design or templating temperature depends on the structure of the conductor as well as the material from which the conductor is made. It is possible to use high temperature alloy conductors which can withstand temperatures up to 210°C. In this case the templating temperature can be increased to that level with the corresponding current rating. Whilst it is correct that a smaller conductor at a higher templating temperature has a lower initial cost than a larger conductor at a lower templating temperature for the same thermal rating, the larger conductor may be preferred due to lower life cycle losses. Normally, due to joule heating losses, high temperature conductors are employed where the thermal rating of the line is critical for short periods of time. They are generally more expensive than the conventional ACSR conductors and require a specialised application to warrant the additional expense.

3.6.1 Convective Cooling [Stephen, 1992]

Of the components described in equation [3.25], the convective cooling component is by far the most influencial in determining the conductor rating. It is therefore covered here in more detail.

The convective cooling component is

$$P_c = \pi\lambda_f(T_s - T_a)Nu \qquad [3.26]$$

Where:

ν_f $= 1.32 \cdot 10^{-5} + 9.5 \cdot 10^{-8}\, T_f$

λ_f $= 2.42 \cdot 10^{-2} + 7.2 \cdot 10^{-5}\, T_f$

Pr $= 0.715 - 2.5 \cdot 10^{-4}\, T_f$

g $= 9.807$ (m/s^2)

T_f $= 0.5(T_s + T_a)$

T_a = ambient temperature (deg C)

T_s = surface temperature (deg C)

$$Nu = B_1(Re)^n \quad [3.27]$$

The Reynolds number, $Re = \rho_r VD/\nu_f$, where V is the wind velocity (m/s), ν_f is the kinematic viscosity (m^2/s) and ρ_r is the relative air density ($\rho_r = \rho/\rho_0$, where ρ is the air density at the altitude in question and ρ_0 is the air density at sea level)

B_1 and n are constants depending on the Reynolds number and conductor surface roughness $R_f = d/[2(D-d)]$, found in table 3.3.

Surface	Re		B_1	n
	from	to		
Stranded all surfaces	10^2	$2.65 \cdot 10^3$	0.641	0.471
Stranded $R_f \leq 0.05$	$> 2.65 \cdot 10^3$	$5 \cdot 10^4$	0.178	0.633
Stranded $R_f > 0.05$	$> 2.65 \cdot 10^3$	$5 \cdot 10^4$	0.048	0.800

Table 3.3 Constants for calculation of forced convective heat transfer from conductors with steady crossflow of air

The wire diameter *d* should be the outer layer wire diameter (usually non-ferrous).

The conductor diameter *D* should be the overall diameter despite the fact that a stranded conductor may have a surface area of 40 - 45 % greater than a smooth conductor of the same diameter. This is because the boundary layer detaches from each wire and re-attaches at the next, thus forming stagnant zones at the interstices. The increase, with regard to forced convective cooling, between stranded and smooth conductors is a function of the roughness and the Reynolds number.

3.6.2 Rating Of Bundles.

The rating of a bundle is determined from the summation of the rating of the sub-conductors. The important fact to note is that for the same aluminium area, it is possible to have one conductor with a large diameter or many smaller conductors with smaller diameters. Although the cooling for the larger conductor is greater due to the higher Reynolds number, the rating for a bundle of smaller conductors can be higher than the single conductor as shown in the following table:

Conductor	Number in bundle	Diameter of conductor (mm)	Al Area of bundle (mm^2)	Total rating (A) (50°C)	Cost/m of bundle	Amps/Rand invested.
Zebra	1	28.62	428.88	642	R38.06	16.86
Wolf	2	18.13	316.12	756	R35.84	21.09
Hare	3	14.16	314.94	876	R15.18	57.70

Table 3.4 Increase in thermal rating using smaller conductors with more sub-conductors in a bundle.

As can be seen from table 3.4, it is possible to increase the thermal rating with lower aluminium area and cost by a factor of greater than 3 by using smaller conductors in the bundle.

3.7. CONCLUSION

The AC parameters that affect the ability of the line to transmit power over long distances are primarily the R, X and B values. The thermal rating can be affected by the height above ground as well as the conductor choice which affects the sag/temperature relationship of the conductor where the sag is the distance from an imaginary line linking the attachment points of the conductor to the lowest point on the conductor catenary. The optimal line requires a low X, high B and low R. In order to achieve this, it is important to realise the constraints as far as corona and mechanical loading are concerned. The table below indicates the relationship between SIL, corona, mechanical loading and thermal rating, where:

"Bad" implies that the option chosen will require that parameter to be studied in depth and mitigation action taken.

"Good" means that the parameter will be favourably influenced by action (e.g. the SIL will be higher with a decrease in phase spacing).

"Neutral" means that the parameter chosen will not be affected by the choice of action.

	SIL	Corona	Mechanical loading	Thermal rating
Phase spacing decrease	Good	Bad	Good	Neutral
Large Al area/cond (less conductors)	Bad	Bad	Good	Bad
Diameter bundle increase	Good	Bad	Bad	Neutral
High steel content	Neutral	Neutral	Bad	Good

Table 3.5 Relationship between actions taken in line design and effect on SIL, Corona, Mechanical loading and thermal rating.

CHAPTER 4

OPTIMISING AC LINE DESIGN

4.1. INTRODUCTION

The AC parameters have been discussed in chapter 3. Table 3.5 indicated the effect on the different parameters by performing certain changes in the line design such as increasing bundle spacing. In order to determine the objective method of optimising line designs it is important to understand the steps required in optimising line designs. These steps are covered in this chapter.

4.2. OPTIMISING LINE DESIGN

A line is a device that transmits power over long distances ("long" in this instance in comparison to a busbar which transmits power over extremely short distances). It is a system of towers, foundations, hardware, insulators and conductors. Each of the components that make up the line affects each other and cannot be optimised on its own. Thus, for example, conductor optimisation cannot be performed in isolation. Optimisation is therefore an iterative process to ensure the overall design is an optimal one.

The optimisation process would be initiated with the purpose of the line that is being designed.

The purpose of the transmission line is to transfer a certain power over long distances. The information required in order to design the line is the power that needs to be transferred but not only the average power but the normal and emergency power transfer requirements of the line. The load profile expected on a daily weekly and annual basis also required.

- The average power is required to determine the aluminium area or best conductor selection based on the initial cost and cost of losses.
- The normal (network without any faults or outages) power requirements are used to determine the average power over the life of the line.

- The emergency power transfer is the power the line is required to transmit under contingency conditions (n-1) when an element of the network is out of service.

- The load profile on a daily basis allows the conductor temperature to be determined taking into account the wind, solar and ambient temperature at that time.

- The shape of the profile will determine the cost of losses as well as the risk of exceeding the conductor design or templating temperature. A peaky profile allows for smaller conductor cross sectional areas as the cost of losses are lower (function of the area under the curve) [Stephen, 1992]

- The annual load profile will indicate whether the line loading peaks in winter where the ambient temperatures will be cooler thus allowing a lower templating temperature to be determined.

The parameters such as load forecast are dependent on a number of external factors such as the economy, thus the certainty of the figures may be unknown. The designs therefore need to be robust enough to cater for the variances in the load from a growth and load profile perspective.

The planners use the model of the line described in chapter 3 to determine, via load flow analysis, the required network solution. The model used in the analysis will assume certain R, X and B values.

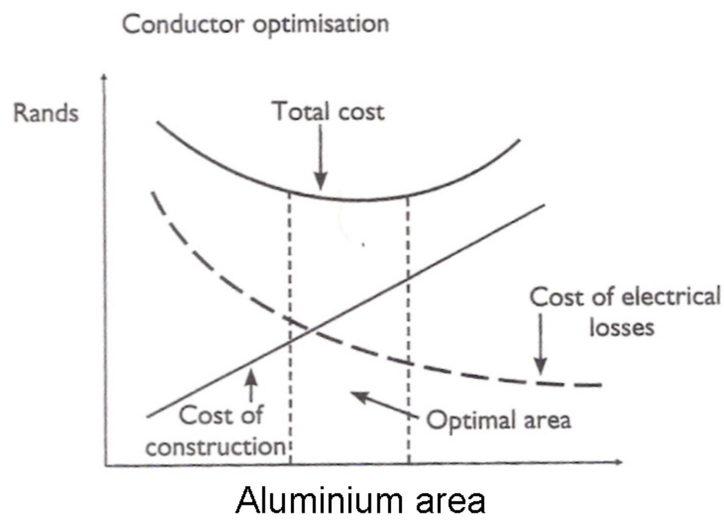
The planners thus need to define for the designers, the R,X and B ranges that can be accommodated as well as load profile (daily, weekly, annually) expected over the life of the line.

From this information initial step is to determine the aluminium area required based on the average power required and the estimated initial and life cycle cost of the line. The method to be used in determining this is the Kelvin's Rule [Muftic, 2005 ch 15 p 333] as stated below.

The statement made by Lord Kelvin in the late 19th century that is still applicable today states as follows:

"the most economical area of conductor is that for which the annual cost of energy wasted is equal to the interest on that portion of the capital outlay which may be considered as proportional to the weight of the conductor"

This is depicted in the graph below:-



Graph 4.1 Graphical expression of Kelvin's rule.

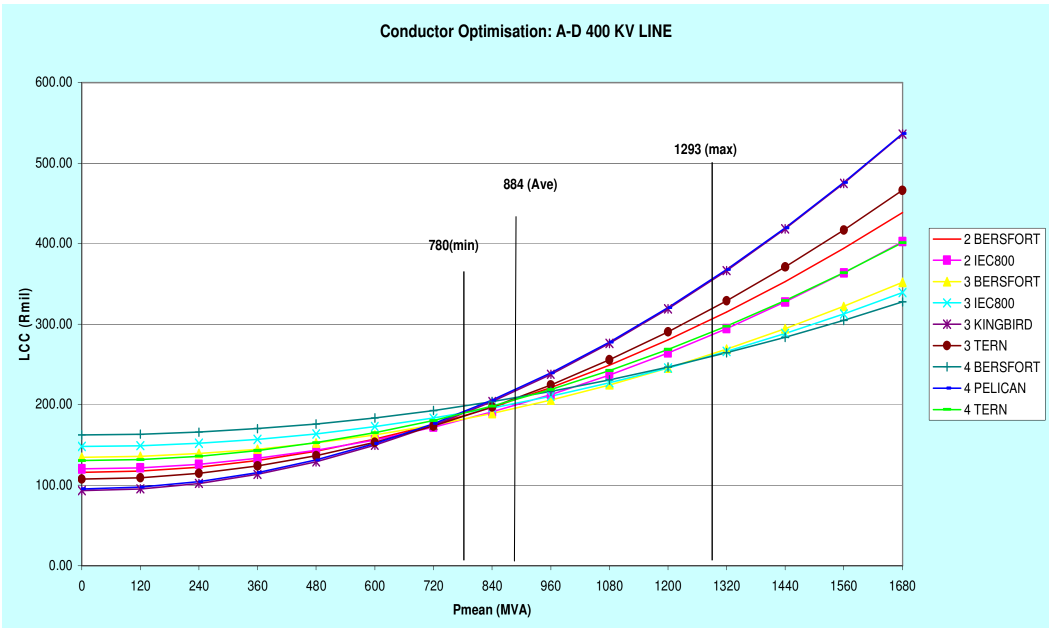
In order to draw the graph the cost of construction and cost of losses need to be determined. In order for the cost of construction to be established it is necessary to decide on a range of possible line designs and cost them. This is derived from previous line designs as well as using tables for the conductor rating which is available in the conductor manufacturer's catalogues (normally deterministic rating [Stephen, 1992])

Utilities normally have a range of tower families that can be used to support the conductor types selected. The tower families will provide for phase spacings from which the R, X and B parameters can be determined using the theory explained in chapter 3.

Tower families are normally called as such as they are a range of towers for a specific application and conductor type. In Appendix 2 the number normally refers to the family or tower series such as 517. The numbering format varies between utilities. In the case of Eskom, the 500 series of families refers to the 400kV range of towers. The 517 series is desgined for a twin Bersfort conductor. The letter following the number describes the tower itself. Normally the closer the letter is to "A" the less strength the tower has. For example a 517A tower is a suspension tower that cannot cater for any angles. The 517E tower is a strain tower and can cater for loads due to an angle or dead end.

These tower and conductor types can then be used to determine the line costs. These will be approximate costs as the soil conditions and line length will not be accurately known. It will provide an idea of the conductor ranges that could be used for the proposed line.

Once a group of options relating to conductor type, phase spacing, tower and foundation types are assumed and costs can be depicted as a function of the mean expected power transfer as shown in the graph below.



Graph 4.2 Mean Power as a function of Life Cycle Cost (LCC) [Vajeth, 2004]

The graph indicated the range of power transfer for which conductor combination may prove the lowest LCC which is a variation on Kelvin's law. In the range of mean power transfer in this case, from 780MVA to 884MVA, triple "Bersfort" (A1/S1A 48/7 687mm^2) (Refer Appendix 1) conductor combination appears to provide the design with the lowest LCC.

Vajeth [2004] describes in his paper that there are steps to optimise the conductor selection. Vajeth [2004], fails to acknowledge in the paper that the LCC depends on the tower, conductor and foundation selection and not only conductor selection. The paper also indicates steps which should be followed in the optimisation of conductors. This is shown below.

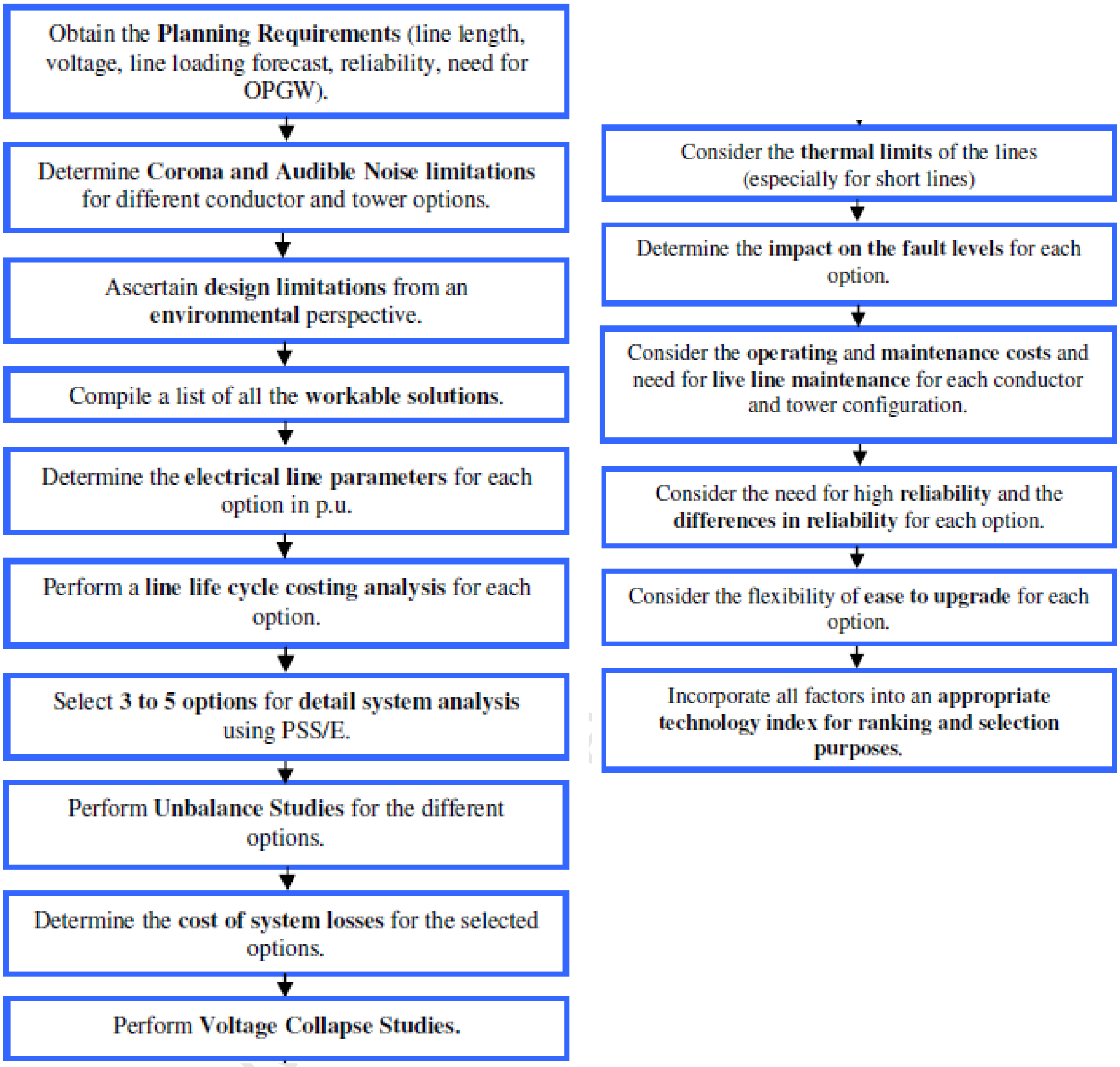


Fig 4.1 Optimisation process as described by Vajeth [2004]

The process is described as a "conductor" optimisation whereas it does not really optimise the conductor but rather narrows the possible conductor, tower and foundation options available. In understanding the conductor selection a further, more detailed analysis is required.

4.2.1 Factors Relating to Conductor Choice

The conductor consists of a current carrying portion and a mechanical load bearing portion. There is often a combination of electrical and mechanical load bearing where the conductor is made up of a mechanically strong conductive alloy. These alloys normally exchange conductivity for strength with the higher the conductivity the lower the strength. National Grid changed the conductor type on its Zebra lines [Tunstall, 2000] with aluminium alloy Rubus 500mm^2 (nominal equivalent aluminium area). This enabled an increase in the rating of the conductors and prevented new lines having to be built. In another example [Tunstall, 2000] the UK faced a situation where twin Zebra conductor lines were placed in series with quad Zebra conductors. They thus had to choose a conductor which could be placed on the existing towers and carry as much current as the quad conductor lines. A gapped conductor (GZTACSR) (refer Appendix 1) was chosen, which has a very small variation of sag to temperature within the same cross sectional area of previous conductors (Zebra).

The load on the tower, due to wind, is a function load on the conductor, which in turn, is a function of the conductor diameter. If the cross sectional area is increased (thus increasing the diameter) in comparison to the previous conductors, there could be a need to strengthen the towers. This is often not possible due to environmental constraints or could be prohibitively expensive.

According to IEC [2003] the load on the conductor is given as:-

$$A_c = q_0 C_{xc} G_c G_L dL \sin^2 \Omega \qquad [4.1]$$

Where:

A_c is the load in newtons N due to the effect of the wind pressure upon a wind span L, applied at the support and blowing at an angle Ω with the conductors.

q_0 is the dynamic reference wind pressure in Pa which is dependent on the reference wind speed and the roughness factor corresponding to the terrain.

C_{xc} is the drag coefficient of the conductor taken equal to 1.00 for the generally considered stranded conductors and wind velocities.

G_c is the combined wind factor for the conductors which depends on conductor height and terrain categories.

d is the diameter of the conductor in (m)

L is the wind span of the support, equal to half the sum of the length of adjacent spans of the support.

Ω is the angle between the wind direction and the conductor.

The force is that which is imparted on the attachment point due to the wind on the conductor. As can be seen from the equation, it is directly proportional to the diameter d.

In bundle conductors, the total effect (according to IEC [2003]) shall be taken as equal to the sum of the actions on the sub-conductors, without accounting for possible masking effect of one of the sub-conductors on another.

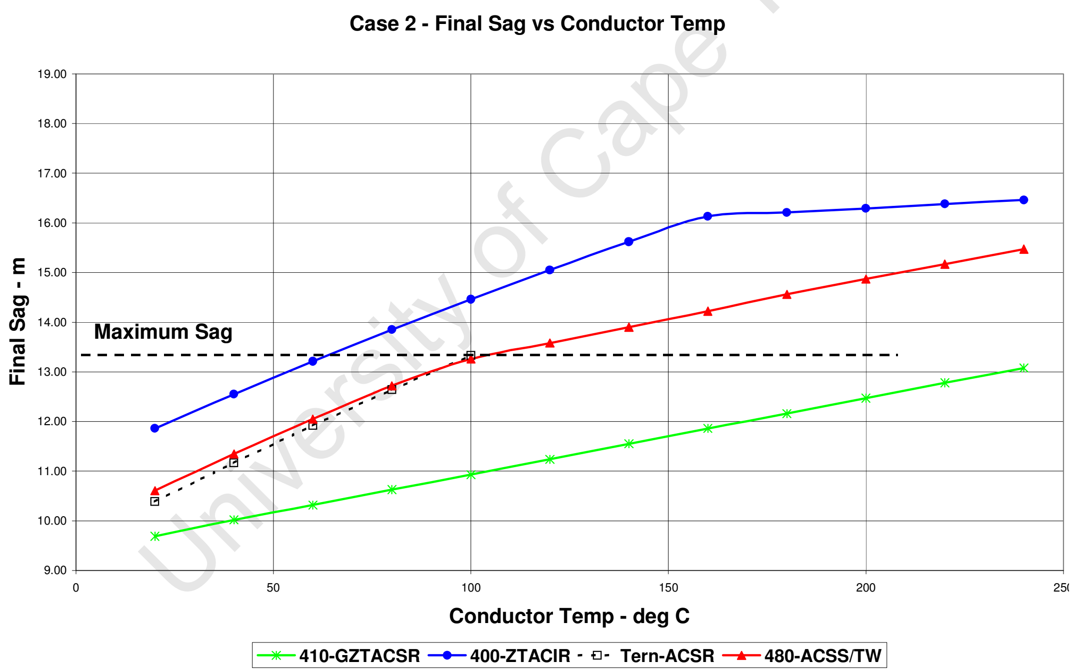
This means that two conductors of diameter 18mm with a combined aluminium area of 300mm^2 will impart the same load as a single 36mm conductor with an aluminium area of 600mm^2. Thus, from a mechanical loading point of view, the less number of conductors in the bundle the better.

The conductor choice has to impact on the tower design (which is a function of the load the tower must take) which in turn has an effect on the foundation design (which is a function of the load the foundation must bear). As a rule, the fewer number of conductors in a bundle and the lower the tensile strength of the conductor, the lower the tower strength required. Corona limitations will dictate the minimum number of conductors in a bundle and the diameter of the conductor.

The life cycle cost (LCC) is a function of the aluminium area of the conductor which is determined from the average power required to be transmitted down the line. The aluminium area then has an input into the number of conductors in the bundle which is a function of the corona inception voltage, which in turn is a function of the bundle configuration, phase spacing and altitude at which the line operates.

The larger the phase spacing the lower the corona inception voltage. The higher the number of conductors in the bundle, the lower the corona inception voltage. Unfortunately the larger the phase spacing, the higher the line impedance and losses (refer Chapter 3). The higher the number of sub-conductors in the bundle, the higher the wind loading on the tower. Thus, the conductor structure needs to ensure maximum aluminium area for the minimum cross sectional area, low mechanical load on towers and ability to carry the normal and emergency current in the specific geographic area. In order for this to be achieved the conductor designs vary. In order to minimise the cross sectional area, conductor stranding can be trapezoidal or "Z" strand which removes any air gaps in the conductor that are present with round wire stranded conductors.

In addition, the current carrying area in the structure is increased by reducing or removing the non carrying strength component. This can be achieved by changing the material to a mechanically strong alloy which is current carrying or by reducing the steel component in the conductor. It is known that only 8% of current flows down the steel core [Morgan, 1982]. Thus if this can be reduced without adversely affecting the mechanical performance it will have the effect of lower cost and lower tensile strength, which will allow for lighter tower designs especially strain towers. The reduction in steel core can be achieved by varying the diameter of the aluminium strands and the steel strands. Thus the stranding is depicted as 45/7 or 42/7 as compared to 54/7 which is the same strand diameter throughout. The 45/7 and 42/7 strandings have lower % component of steel.



Graph 4.3 Sag vs conductor temperature [Douglass, 2004]

In addition to the mechanical and electrical characteristics of the conductor, it is important to determine the relationship between the conductor components that carry the mechanical load as a function of temperature. As the temperature increases the load bearing in the conductor changes from the aluminium to the steel. When the aluminium and steel carry the load the conductor sags at a higher rate than when the steel only carries the mechanical load [Douglass, 2004]. The point at which the load is transferred from the combined aluminium and steel to steel only is the knee point as shown in the graph 4.3 above .

The lower the temperature at which the knee point occurs, the higher the temperature can rise before the maximum sag is reached. Thus, depending on the required sag, the sag temperature relationship of the conductor can be specifically designed. Conductors with low knee points are either annealed aluminium conductors or gapped conductors. The conductors are more expensive than the standard ACSR conductors but allow for increased thermal rating. In addition the construction challenges in stringing a special conductor, such as gapped conductor are difficult to overcome [Tunstall, 2000].

In the graph 4.3, the knee point is the point at which the slope of the sag-temperature curve changes. The lower this occurs the more the conductor temperature sag relationship will follow the steel core. This will result in a higher temperature and lower sag condition. As can be seen from the graph 4.3, the gapped conductor (GZTACSR) has no knee point and the sag is therefore far lower than other conductors for a wider range of temperatures. It was this characteristic that allowed the National Grid to obtain the same rating as quad rating with a twin conductor bundle [Tunstall, 2000].

In conclusion, the conductor designs at present allow for tailor making the conductor parameters to the line design. The conductor optimisation process is interactive and specialised conductor application would be undertaken after estimates made using standard conductors.

4.3. STEPS REQUIRED IN OPTIMISATION

The steps that are required in optimising lines, which includes the iteration with planners, are thus as follows:

a) Obtain requirements from Planners. This includes the following:

- Start and end points for the line.
- Intended line voltage.
- Load peak under normal conditions.

- Load peak under emergency conditions.

- Load profile over the life of the line in terms of daily, weekly and annual load variation.

- Range of R, X & B that can be applied to the line (Planners may prefer to state the standard conductor options that were considered.

- Environmental constraints.

- Cash limitations.

- Reliability requirements.

b) Determine a first pass in relation to the aluminium area by assuming initial cost and calculated cost of losses.

c) Determine, knowing the altitude and the voltage, the possible conductor, bundle and phase spacing options by calculating the corona inception voltage and the voltage gradient and expressing these two figures as a ratio.

d) Develop at least 10 conductor, tower and foundation combinations that will meet the planner's requirements.

e) Take options back to Planners to check if all options do in effect meet the planner's needs. Remove options which are a technical non optimum solution. This is because the designers can develop a number of options based on the assumptions of the planners. The planners are operating in a less certain environment and hence the designers will have a number of possible solutions for them. It is necessary to check with the planners which options will best meet their needs.

f) The remaining design options now need a further analysis and a more detailed design analysis performed.

g) Templating, or design temperature optimisation needs to be undertaken. The emergency rating is normally taken as the parameter to meet with templating temperature increase. Thus small aluminium area conductors with more sub-conductors in the bundle (perhaps with a smaller overall aluminium area) with a higher templating temperature. The larger the overall aluminium area the higher the likelihood of being able to reach the emergency rating with a lower templating temperature. It may be necessary at this point to identify possibilities for special high temperature low sag conductors as shown in graph 4.3. The cost of the line increases with templating temperature for the same conductor bundle. However, it is possible to meet the thermal rating requirements of the line with different conductor and templating temperature configurations.

h) Obtain, via digital terrain modelling, a likely geographical profile for the line. This can be obtained by laser survey techniques taken over possible routes or by using the profile of a line in the area.

i) With the line profile, determine the optimum tower family combination for the selected conductor bundle and templating temperature options.

j) Further refine the tower selection with likely environmental constraints which may affect the tower selection. For example land owners in a certain area may insist on self supporting rather than guyed structures.

k) Re-check options using the more accurate R, X & B values from the tower families selected with planners. The load flow studies need to be performed for each year, or every five years if load and network configurations do not vary too much. The total network losses need to be determined to extract the exact effect the line has on the network (not only the loss on the line) and this information used to determine the graph 4.2 of P_{MEAN} vs LCC.

l) The group of designs that meet the LCC as well as meets planner's requirements needs to be objectively rated to determine the final 2-3 designs that can be used for more detailed design process.

m) The detailed designs on the actual line route and geographical profile need to be done.

n) Other options which are hard to quantify, such as maintenance preferences, stock levels and range of materials are then taken into account from which a single tower, conductor and foundation combination is chosen to be taken to the detailed design stage.

The detailed design phase may include design and testing of a new tower design as well as specialised research for example, in joining and stringing of specialised conductors as described in [Tunstall, 2000]. In certain cases it may be beneficial to design a conductor specifically for the project.

The step (l) where the possible designs are objectively rated is critical. Without an objective rating per design it is not possible to rationally choose the best group of options. It is likely that there will be a large amount of discussion with no decision, or a sub optimal decision being taken. The nature of the line design team is that it is a multi-disciplinary team consisting of civil, geotechnical, electrical and mechanical engineers. They may tend to prefer the solution best suited to their discipline. The electrical engineers tend to prefer a large number of sub-conductors in the bundle with small phase spacing. Mechanical engineers prefer the lowest possible sub-conductors in the bundle with a wider phase spacing allowing for lower guyed loads and tower member loads. This conundrum highlights the need for an objective indicator whereby the overall function of the line is used to determine the best group of solutions. Without such a measure disciplines may optimise their area of the line without consideration for the implications of their decisions on the line function.

The development of an objective measure is covered in the next chapter.

CHAPTER 5

PARAMETERS REQUIRED FOR OBJECTIVE DETERMINATION

OF OPTIMAL LINE DESIGNS

5.1. NEED FOR AN OBJECTIVE MEASURE

The planner's requirements of a line can be met in numerous ways to different extents. For a particular power transfer, there are many different tower, conductor configurations and templating temperatures that can meet the power and voltage criteria required by a planner.

Line impedance can be realised by the number of conductors/bundle, phase spacing and phase configuration (chapter 3).

The higher the number of sub-conductors per bundle, the higher the SIL, and the closer the phases are together, the higher the SIL. However, the higher the number of conductors per phase, the higher the wind loading which results in a higher tower loading and foundation loading.

The higher the number of conductors per bundle the higher the corona inception voltage for a given phase spacing. Therefore, the higher the conductors per bundle, the smaller the allowable phase spacing, and the higher the SIL. The thermal rating is also higher with a large number of sub-conductors for a given conductor aluminium area. The drawback is the higher mechanical loading and tower costs.

Once the bundle and phase spacing options are determined the resulting impedance options can be fed back to the planner to determine the effect of the line design on system losses.

The decision as to which line design option to finally decide on is a very difficult one. For a particular impedance and load transfer capability there can be many different conductor, bundle, tower, and foundation combinations. The task is made more difficult if the network planners are unsure of the load forecast relating to the purpose of the line in the network.

It is thus necessary to attempt to devise an objective method whereby the best group of line designs can be determined. From the best group a final decision can be reached looking at present standards, maintenance practices and availability of capital.

In the following tables examples are taken from an actual line design covered in an internal report for Eskom by a subsidiary of Eskom enterprises, Trans Africa Projects (TAP) [TAP, 2008]. This report covers the conductor selection and optimisation for a 400kV line in the Eastern Cape Province of South Africa. The line forms the first section of two links linking two 400kV networks from the Kwa Zulu Natal province to the Cape Province and is primarily aimed at supplying load to the Mthatha area. This section of line is approximately 165km long and will be a radial line initially. The purpose of showing the results here is not to go into detail of the calculations and assumptions but rather to indicate the need and use of an objective indicator with actual examples.

Year	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Normal Load (MVA)	243	295	330	491	464	474	423	431	440	449	458
Emergency Load (MVA)	307	353	319	607	575	595	531	542	552	563	575

Year	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**
Normal Load (MVA)	467	476	486	496	506	516	526	536	547	558	569
Emergency Load (MVA)	586	598	610	622	635	647	660	673	687	701	715

Year	**2033**	**2034**	**2035**
Normal Load (MVA)	581	592	604
Emergency Load (MVA)	729	744	758

Table 5.1 Requirements From Planner

CASE	CONDUCTOR BUNDLE	CONDUCTOR IEC-CODE	CONDUCTING AREA PER BUNDLE (mm^2)	CURRENT DENSITY PER BUNDLE, (A/mm^2)	OVERALL CONDUCTOR DIAMETER (mm)	SUB-CONDUCTOR SPACING (mm)	TOWER TYPES
1	3 x Tern	403.77-A1/S1A-45/3.38+7/2.25	1211	0.57	27.00	450	529A, 528C, 528D & 517 Series
2	4 x Kingbird	323.01-A1/S1A-18/1/4.78	1292	0.53	23.90	450	529A, 528C, 528D & 515 Series
3	2 x Bersfort	687.36-A1/S1A-48/4.27+7/3.32	1375	0.50	35.58	380	529A, 528C, 528D & 517 Series
4	3 x Greely	469.6-A2-37/4.06	1409	0.49	28.14	450	529A, 528C, 528D & 517 Series
5	6 x Pelican	242.31-A1/S1A-18/1/4.14	1454	0.47	20.70	380	529A, 528C, 528D & 517 Series
6	2 x IEC-800	800.00-A1/S1A-84/7/3.48	1600	0.43	38.30	380	529A, 528C, 528D & 517 Series
7	4 x Tern	403.77-A1/S1A-45/3.38+7/2.25	1615	0.43	27.00	450	529A, 528C, 528D & 518 Series
8	3 x Bluejay	565.49-A1/S1A-45/4.00+7/2.66	1696	0.41	31.98	570	529A, 528C, 528D & 518 Series
9	4 x Greely	469.6-A2-37/4.06	1878	0.37	28.14	450	529A, 518 Series
10	6 x Kingbird	323.01-A1/S1A-18/1/4.78	1938	0.36	23.90	380	529A, 518 Series
11	3 x Bersfort	687.36-A1/S1A-48/4.27+7/3.32	2062	0.33	35.58	570	529A, 518 Series
12	4 x Bluejay	565.49-A1/S1A-45/4.00+7/2.66	2262	0.31	31.98	570	529A, 518 Series
13	3 x IEC-800	800.00-A1/S1A-84/7/3.48	2400	0.29	38.30	570	529A, 518 Series

Table 5.2 Different Solutions That Could Meet the Planner's Requirements detailed in table 5.1.

The examples shown in Table 5.2 indicate that there are at least 13 different types of conductor, tower (refer appendix 2) and foundation combinations that could meet the electrical requirements as prescribed by the planner in table 5.1. These are also using existing towers of a particular type mainly cross rope suspension. If other tower types were used, such as self supporting, there would be another 13 options at least. This would increase further if a tower were designed specifically for the project.

In deciding which option to use, it is necessary to narrow the number or scope of the options by objective analysis.

5.2. PARAMETERS TO CONSIDER

The design alternatives for overhead lines as covered in Chapter 3 to meet the AC parameters can be covered by a certain parameter. The planners would have specified certain load requirement as well as R,X and B parameters for the network. The parameters to consider are covered in the following sections.

5.2.1 Load Requirement

The load requirement is met by the conductor type as well as the thermal rating of the line. The conductor bundle selection will be determined by the corona limitations and the voltage and stability criteria. If load capability is the only criteria, it can be achieved by a smaller aluminium area. The following example, taken from the rating table used by Eskom, [2000] amplifies this issue. Note that the conductor options are not limited to ACSR as shown in chapter 4, there are many different conductor types that can be considered:

	Temp Deg C	Normal Amps	Emergengy Amps
Wolf (150mm^2)	50	378	501
Wolf	60	473	602
Wolf	70	548	683
Wolf	80	610	751
Zebra (428mm^2)	50	642	859
Zebra	60	818	1049
Zebra	70	963	1203
Zebra	80	1080	1325

Table 5.3 Templating Temperature and Ampacity

The above table indicates that for different templating temperatures the current varies for the same conductor type. If the load requirement was 1600 MVA for a 400 kV line, the current per phase is 2309 A. The load can be met with a quad wolf bundle which will meet corona requirements (Eskom used quad wolf as a standard in the 1990's at altitude of 1800 m). The templating temperature to allow for 2309 A is 80^{o}C templating temperature with a total aluminium area of 600 mm^2. The alternate could be triple zebra at 50^{o}C with an aluminium area of 1284 mm^2. The twin zebra option would not meet the corona audible limitations in terms of the SABS 60103 [1993] at 400 kV. The resistance losses are far more with the quad wolf option than the triple zebra option although both will meet the load requirement. Note that the high temperature conductors have not been included in the example, the reason being that the principal is the same, high temperature conductors will enable ratings to be determined at temperatures up to 210^{o}C.

5.2.2 Impedance (R, X and B)

The R, X and B parameters are determined by the bundle diameter, conductors in the bundle as well as phase spacing as covered in chapter 3. The impedance is best represented by the surge impedance loading as described in chapter 3. The planners could specify the SIL range or the R, X and B values. Often the latter is easier to specify as the R, X and B parameters are used in the load flow calculations and may be readily available. The SIL parameter can be met by a number of bundle configuration, phase spacing, conductor types and phase layout (inverted delta, or flat configuration for example).

Thus, by comparing the SIL of the different designs, the designer can get an idea of the effect of the phase spacing, sub-conductors, bundle diameter and phase configuration on the overall line impedance. An example of the calculation, based on a suspension tower (type 529A) suitable for use at altitude of 1800 m, is shown in Table 5.4. The phase configuration is the same for all options and the SIL is a function of the bundle type. The higher the SIL, the lower is the overall impedance.

Case	Conductor bundle	Per Unit Positive Sequence Impedances (P.U./km)			Surge impedance load – SIL (MW)
		R	X	B	
1	3 x Tern	0.0000152	0.0001662	0.0069087	645
2	4 x Kingbird	0.0000141	0.0001518	0.0075676	706
3	2 x Bersfort	0.0000136	0.0001885	0.0060997	569
4	3 x Greely	0.0000127	0.0001660	0.0069326	646
5	6 x Pelican	0.0000125	0.0001373	0.0083721	781
6	2 x IEC-800	0.0000119	0.0001870	0.0061495	573
7	4 x Tern	0.0000114	0.0001506	0.0076318	712
8	3 x Bluejay	0.0000110	0.0001578	0.0072994	680
9	4 x Greely	0.0000096	0.0001504	0.0076537	713
10	6 x Kingbird	0.0000094	0.0001364	0.0084332	786
11	3 x Bersfort	0.0000091	0.0001563	0.0073686	687
12	4 x Bluejay	0.0000083	0.0001419	0.0081265	757
13	3 x IEC-800	0.0000079	0.0001554	0.0074171	691

Table 5.4 R, X and B Values Of The Design Options For A Specific Tower Type

The SIL can thus be used as a parameter to compare the impedance values of the various design options as this combines the R, X and B parameters in such a way that the power transfer is related to it in a single figure.

5.2.3 Inclusion Of Voltage Drop

For overhead lines with a voltage above 132 kV, it is not often that voltage drop is a parameter that governs the power transfer of the line. However, lines of voltages below 132 kV, are often subject to voltage drop constraints.

The voltage drop is a direct function of the impedance of the line and the position of the line in the network, and the load and power factor. The method of analysis prescribed by Vajeth [2004] actually proposes that the losses are determined by actual load flow studies in the network, so that the actual power flow down the line and hence the losses can be accurately determined. In doing this the MVA transfer limit will be determined either by the stability of the network or by the voltage drop on the line.

Thus by performing load flow studies for each of the line design options, it is possible to determine the MVA that can pass down the line in a certain network and generation configuration. The planners need to assist in this regard to ensure that the load flow studies performed are in line with their original assumptions and analysis in proposing the line.

It appears therefore that for the determination of voltage and stability transfer limits, it is necessary to perform actual load flows to determine the maximum power transfer down the line, based on voltage and stability constraints.

5.2.4 Initial cost of options

The initial cost of the project is also important in determining which options should remain for further analysis. In this regard the table 5.5 below indicates the cost of the options. In the internal report on the analysis of the options it was stated that “It is worth noting that the life cycle costs of triple Bersfort, the six-bundled Pelican, quad Greely, triple IEC-800, the six-bundled Kingbird and quad Bluejay are greater than the life cycle costs of twin IEC-800 by values ranging from 17.9% to 31.8%. These four options are excessively more expensive than the best option. Considering these options for further analysis is not economically justifiable”.

CASE	CONDUCTOR BUNDLES	CAPITAL INVESTMENT COST (Rm)	TOTAL LINE LOSSES COST (Rm)	LINE LIFE CYCLE COST (Rm)	LLC RANKING	DEVIATION FROM BEST OPTION (%)
1	3 x Tern	270	126	396	4	3.2
2	4 x Kingbird	273	117	390	3	1.7
3	2 x Bersfort	271	113	384	2	0.1
4	3 x Greely	303	105	409	6	6.5
5	6 x Pelican	352	104	455	9	18.7
6	2 x IEC-800	285	98	384	1	0.0
7	4 x Tern	337	94	432	7	12.5
8	3 x Bluejay	311	91	402	5	4.8
9	4 x Greely	414	79	493	10	28.6
10	6 x Kingbird	426	78	504	12	31.5
11	3 x Bersfort	377	75	452	8	17.9
12	4 x Bluejay	437	68	506	13	31.8
13	3 x IEC-800	436	66	502	11	30.8

Table 5.5 Initial and life cycle costs of options.

The reason the options are more expensive is almost entirely due to the heavier conductor selection which results in an increased conductor cost, tower cost (due to the heavier wind load and conductor weight) as well as the related foundation and erection costs per tower.

5.2.5 Power Transfer Capabilities

The SIL calculated above does not fully describe the power transfer capabilities of the design options. It is necessary to evaluate the capabilities using load flow calculations in the network in which the line is to be built. This was performed, for example, on the design options for a 400 kV line in the Eastern Cape Province in South Africa. The results are shown in Table 5.6. The capability of some higher cost options were also calculated but are not included here. It should be noted that the line in question was part of an integrated network and not a radial line. Thus it was possible to determine the n-1 contingency figures.

Case	Conductor bundles	Power transfer under n-1 contingency	Power transfer under n-1 contingency with 100 mvar capacitor bank installed (MVA)	Additional power transfer (MVA)	Relative power transfer normalised to 1885.36 MVA	Capacitor bank size to make up additional power transfer (MVAR)	SIL	Cost to make up additional power with shunts (Rm)
1	3 x Tern	1853.72 (8)	1929.99 (6)	76.27	31.64	41.48	645 (6)	9
2	4 x Kingbird	1885.36(1)	1933.02 (4)	47.66	0.00	0.00	706 (2)	0
3	2 x Bersfort	1873.95 (7)	1927.16 (8)	53.21	11.41	21.44	569 (7)	4
4	3 x Greely	1878.82 (5)	1932.47 (5)	53.65	6.54	12.19	646 (5)	3
6	2 x IEC-800	1874.50 (6)	1927.88 (7)	53.38	10.86	20.34	573 (8)	4
7	4 x Tern	1880.59 (3)	1933.72 (3)	53.13	4.77	8.98	712 (1)	2
8	3 x Bluejay	1885.10 (2)	1933.72 (2)	48.62	0.26	0.53	680 (4)	0
11	3 x Bersfort	1880.36 (4)	1934.03 (1)	53.67	5.00	9.32	687 (3)	2

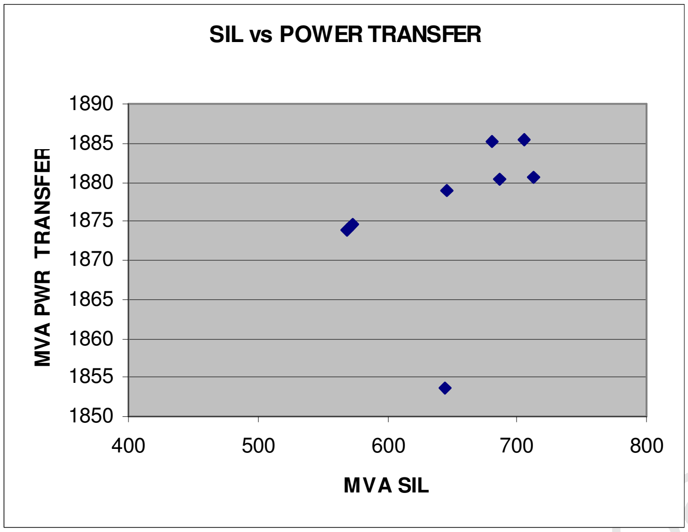
Table 5.6 Table Indicating The Power Transfer Capability Of Eight Design Options (Rank In Brackets)

In this case, the currents in the conductors are in the 50^{o}C and 60^{o}C templating temperature rating range and therefore, the resistance compensation for the temperature in performing the load flows is not considered necessary. However, if a smaller sized conductor with a templating temperature of above 80^{o}C is used, it is advisable to perform load flow studies with a higher resistance figure to determine if this has an effect on the ranking.

The n-1 contingency implies any contingency that will affect the load in the line under study. This could be generators being switched out, lines supplying the area being switched out etc. The n-1 obviously applies to an integrated network or a network with generation that will affect the flow.

Note from the above that design options 5, 9, 10, 12, 13 were not considered for further analysis due to the high costs of these options in relation to the others (as explained in section 5.4)

The above Table 5.6 indicates that the option with the highest SIL is not necessarily the option that will transfer the highest load. This is dependent on the impedance of the network. However, the options with the highest SIL are still among the options with the highest transfer options. These are design options 7, 2, 11 and 8. These options result in the highest power transfer of all options. Thus the SIL may not indicate the best option that will result in the highest power transfer but will give an indication of the group of design options that will provide the highest transfer.



Graph 5.1 SIL vs Power Transfer

The above Graph 5.1 indicates that there is a relationship between the SIL and power transfer although the relationship is not strictly linear. The outlier, referring to option 1, the triple Tern, seems to indicate an error in the load flow analysis and should be checked. The top 4 options are clearly visible at the top right of the graph.

5.2.6 Life Cycle Costing

The life cycle costing is a method to determine the lowest cost design option over the life of the asset. Life cycle costing takes into account the initial cost as well as the cost of losses and maintenance over the life of the asset. The cost of losses are determined from the load factor as well as the long run marginal cost of generation which indicates how much the utility will pay for every additional MW of loss on the line.

In order to compare the options, however, it is necessary to understand the saving to the network that the line results in. Thus, it is not sufficient to determine the loading of the line in isolation but rather to calculate the change in losses of the system. This is because the line will result in a different power flow in the network. The sharing of the power in the network may result in certain design options creating more losses in a meshed network than they would on a radial line.

The analysis can be enhanced further by including the cost of compensation to increase the power flow of the line in the network. This will indicate that, if a shunt capacitor is installed on the system that the power may be increased for some options for minimal increase in costs. A similar exercise could be undertaken using series compensation for longer lines. In Table 5.5 the power transfer under n-1 contingency with 100 MVAr capacity bank installed is shown. The capacitor bank is determined from the load flow studies indicating the VAR generated by the capacitor bank Table 5.6. The costs are estimates made on an amount per MVAR and may not necessarily reflect the standard capacitor bank sizes. It does, however, give an indication of the additional cost for the compensation.

Thus, the life cycle cost could include the system losses, maintenance and compensation cost to obtain the desired power flow criteria. The maintenance cost on the options chosen are considered the same hence, the LCC is calculated without specifying the maintenance cost.

Case	Conductor bundles	Capital investment cost (Rm) CIC	Life cycle benefit from reduced system losses (Rm)	Cost to make up additional power with shunts (Rm)	Overall life cycle cost (Rm) LCC	Position	Deviation from best option (%)
1	3 x Tern	-270	1055	-9	776	3rd	3.4
2	4 x Kingbird	-273	1077	0	804	1st	0.0
3	2 x Bersfort	-271	1045	-4	769	5th	4.3
4	3 x Greely	-303	1080	-3	775	4th	3.6
6	2 x IEC-800	-285	1058	-4	768	6th	4.4
7	4 x Tern	-337	1100	-2	761	7th	5.4
8	3 x Bluejay	-311	1095	0	784	2nd	2.5
11	3 x Bersfort	-377	1112	-2	733	8th	8.8

Table 5.7 Life Cycle Cost With Additional Compensation Cost Added

5.2.7 Constructability

The design options in this case use standard conductors at present in use in the utility. The tower types have also been used on a number of projects in the past. The one issue that needs to be taken into account is stringing of fairly light conductor, such as Kingbird which is an 18/1/4.78 construction meaning it is 18 strands of aluminium and 1 strand of steel all 4.78mm in diameter (refer Appendix 1). The diameter to weight ratio is an indicator of the ease of these conductor in relation to stringing. The lower this ratio the easier is the stringing of conductor as the higher the ratio the more the conductor is prone to movement in the wind. As mentioned previously the higher the diameter the more the wind load on the conductor hence the more the conductor will move when exposed to a certain wind pressure.

The Table 5.8 below uses the three conductors that includes the top three in accordance with the Table 5.7. The additional conductor "Zebra" is 428 A1/S1A 54/7/3.18 has been used extensively up to 6 bundle (765kV) in Eskom and is known as a conductor that is relatively easy to string even in bundles with higher numbers of sub-conductors.

Conductor	Weight kg/mm	Diameter mm	Dia/weight mm^2/kg
Kingbird	$1.030*10^{-3}$	23.9	23204
Tern	$1.336*10^{-3}$	27.03	20217
Bluejay	$1.870*10^{-3}$	38.9	20802
Zebra	$1.621*10^{-3}$	28.6	17643

Table 5.8 Ratio Dia/Weight to Determine Ease of Stringing.

The above table indicates that the diameter to weight ratio for the Kingbird conductor is more than 10% higher than the other options, which means it will be more difficult to string. It is also noteworthy that the ratio for the Zebra conductor is again over 10% lower than the Tern or Bluejay options with the Tern option being slightly better than the Bluejay option. The Zebra conductor is easier to string than these other options.

A higher the number of sub-conductors in a bundle also makes it more difficult to construct the line. In this case the requirement due to power transfer loading is quad Kingbird compared to triple Tern and Bluejay. Thus the increase in sub-conductors as well as the higher diameter/weight ratio makes Kingbird a conductor bundle choice that is harder to construct than other options.

The type of tower as well as equipment used is also a factor in construction. This will vary from line to line and depend on the terrain, soil conditions, weather conditions and environmental constraints. The environmental constraints also refer to the ROW or servitude width, if the width is fairly narrow it will not be possible to use the tower families mentioned in the example given above and a pole or similar narrow servitude design may have to be considered.

In these cases the constraints should be determined up front and the tower family and conductor types determined for analysis after the tower family constraint is specified.

5.2.8 Reliability

The different design options are all designed with the same expected reliability. The tower window or clearances in the case of no tower window are determined using similar overvoltages in all cases as well as the same wind loading criteria according to IEC [2003]. Thus the reliability levels as calculated with standards, such as IEC are incorporated in all design options. However, in some instances, these specifications and guidelines might be insufficient, as has been experienced in certain 400 kV lines on the Eskom network.

For example, it was found in 2005 that the Grassridge-Poseidon 400 kV line using a quad Pelican conductor (242 A1/S1A 18/1 4.14) with a diameter to weight ratio of 26779 mm^2/kg, has caused failure due to conductor movement above that calculated. A report on the line failures [Ghannoumn, 2009] also used a similar ratio of diameter to weight ratio with diameter in mm and weight in N/m. This indicated Pelican to have a higher ratio than Tern. Of interest in the report is that the movement of the phase conductors was observed to be more erratic than that of quad Zebra, a heavier conductor. In the case of the Zebra, the movement under wind was more damped and the conductors did not move around under the pressure of the wind but maintained a steady position. In the case of Pelican the conductors were seen to move around erratically in the wind thus increasing the probability of flashover. Due to this Ghannoumn [2009] recommended that an insulated crossarm be used. This is shown below.

Figure 5.1 Existing configuration

The arrow pointing east is also of relevance in this case as the line traversed north south and crossed valleys running east west. Thus wind channelling was possible with winds blowing from an easterly direction. This wind direction would cause maximum conductor swing.

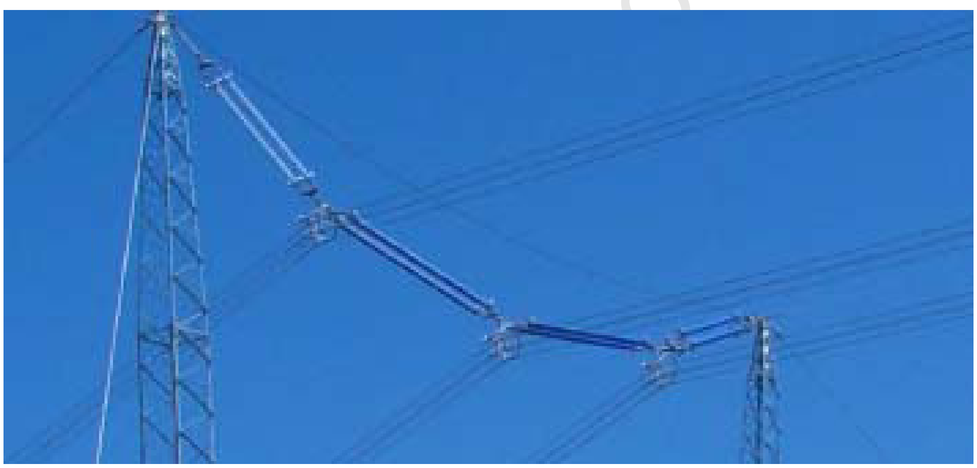


Figure 5.2 Proposed Configuration

This recommendation is unusual in that normally weights attached to the conductors would be used. In this case, however, due to the erratic movement of the conductors as well as the possibility of mid span flashover, the configuration in figure 5.2 was proposed. This is a very costly solution and indicates that the conductor choice initially was incorrect.

Similar poor performance was experienced in the Western Cape using a triple Kingbird on a 400 kV line which also experienced conductor movement larger than calculated. This was particularly on the strain tower jumpers which were exceedingly long. This was solved with weights being installed on the jumpers. Elsewhere single Kingbird lines have exhibited no such issues although these lines are at a lower voltage with different clearance and overvoltage characteristics which may have played a role in the increased reliability of the line.

From experience in use of these high diameter to weight ratios, it appears that the bundle configurations of triple or more sub-conductors may be problematic with ratios of 23000 mm^2/kg or greater. In these cases extra mitigation to prevent conductor movement needs to be considered which will increase the initial cost of the line.

Mitigation methods that can be used to avoid excessive conductor swing include adding weights to the jumpers in strain towers as well as adding interphase spacers in the line. These are commercially available but represent more items that need to be attached to the conductors on the line thus increasing risk of failure.

Thus, the use of bundles of conductors (2 sub-conductors and above) with high diameter to weight ratios are likely to be less reliable than bundles with diameter to weight ratios of lower than 23000 mm^2/kg.

The reliability requirements for the line need to be specified up front by the planner. In this case the planner may state that the reliability should not be worse than existing lines in the area. The terrain and environmental constraints also need to be specified so that the designers can design the tower family and conductor options that need to be considered for further optimisation.

5.2.9 Line Length

The length of the line will affect the power transfer and the voltage drop of the line. As a parameter in itself it is therefore incorporated into the load flow analysis conducted by the planner. If the line is long, small conductor solutions may not be suitable due to power transfer and voltage drop constraints. It is proposed not to include the line length as a parameter but to realise that the effect of the line length is included in the load flow analysis that needs to be performed by the planners on the different design options.

5.2.10 Mechanical loading

As mentioned previously, electrical engineers would prefer a large number of sub conductors whereas mechanical engineers would prefer a few sub-conductors. The question then arises as to whether mechanical loading should form part of an indicator. When costing a line the mechanical characteristics are apparent in that a solution with a high mechanical loading will cost more than a line with a lower mechanical loading, assuming of course that towers are optimised for the particular conductor bundle and their mechanical utilisation (percentage of actual load seen by the tower to the load capability of the tower). Thus the mechanical loading criteria is included in the initial cost of the line and need not form an additional parameter.

5.3. ASSESSMENT OF LINE DESIGN

In determining the optimal line design for a particular application, we need to ensure that the design meets the planner's criteria for load transfer, voltage, and impedance. These parameters have to be met within the constraints of the planner. These constraints include time and cost.

It is not possible, without some form of combination of parameters, to determine the optimum line design. The lowest cost may not result in the lowest life cycle cost, reliability criteria etc. being met. In combining the parameters there is a risk that some value may be lost. For example if only life cycle cost is considered the thermal rating may not be taken into consideration. The indicator therefore needs to be able to assess all the relevant parameters of the line design covered in section 5.2.

The different indicator types will be covered in the following chapter.

CHAPTER 6

INDICATOR FOR OBJECTIVE DETERMINATION

6.1. PURPOSE OF THE INDICATOR

The purpose of the indicator needs to be determined up front. The indicator, for example could be as simple as a life cycle cost only where the option with the lowest life cycle cost will be the one chosen. Other alternatives could include the initial cost, or a combination of cost and parameters.

It may be difficult to determine what constitutes a good line design. Vajeth [2004] uses the life cycle cost as the main indicator. Stephen [2004] uses a combination of parameters to establish the best line design option based on the input cost and the resultant "outputs" of SIL and thermal rating of lines.

The number of variables and parameters used to determine an optimal line design is very high. As such the indicator should identify the four or five best line design options. From these the final option can be decided by the designers taking into account all aspects. These aspects include stock holding, terrain, current cash situation etc. For the indicator to select the best option there is a need for a number of constraints and limitations to be entered into the algorithm for determination. This is not always practical and the decision may not be accepted by all stakeholders in any event. It is more practical for the indicator to identify the best group of options rather than the absolute optimal solution as there are many parameters such as maintenance preferences, public perception of tower aesthetics, and others that are not possible to objectively model.

An indicator to determine the optimal line group of designs will thus, need to be simple in nature, take as many parameters into account as possible, and clearly indicate which design options are to be taken further for analysis.

The development of different indicators is discussed further in this chapter.

6.2. DIFFERENT INDICATORS

Two options relating to indicator design are reviewed. The first is to take the life cycle cost only, expressed in monetary terms. The second is to look at a composite indicator taking into account more parameters.

6.2.1 Life Cycle Cost

The life cycle cost calculation is shown in the previous section. This covers the initial cost, the maintenance cost, and cost of losses. The cost of additional compensation is a method developed by Vajeth [2004] to indicate a method of comparing "apples with apples" where the designs are normalised in relation to the power transfer of the line in the actual network that the design is to be used.

Note that the SIL and thermal rating are still constraints in the determination of the line design. If the LCC is used as the main indicator, these parameters are not optimised and may not be as cost effective.

6.2.2 Composite Indicator

According to Stephen [2004] the objective measure needs to be a simple score or value that can be understood by designers and shared with non-technical managers. Thus it can be expressed either in form of capital spent or in form of a score which is dimensionless.

The measure needs to reflect the ability of the line design to fulfil the purpose of the line as defined by the planners. The purpose of the line can be described in terms of the load transfer limit as well as the suitability of the electrical characteristics in relation to the network requirements.

The loading transfer limit is dependent on the thermal limit, which is dependent on the design or templating temperature determining the height of the conductor above the ground. The load transfer limit is also a function of the power transfer stability limit.

- The thermal limit can be expressed in terms of the MVA line rating under normal, contingency (one line out for maintenance) and emergency conditions.
- The stability limit is a function of the line impedance which can be expressed as MVA (SIL) or maximum permissible load transfer (MVA).
- The suitability of the line design in the network can be measured by the system losses. This can be reflected either as an MVA figure or as a financial cost which would be determined from the MVAh loss multiplied by the short and long run marginal cost of generation.

The challenge is to combine the parameters into a meaningful index which can be used to determine the best group of designs.

The indicator needs to take into account the main factors relating to line design. These are the life cycle cost, the initial capital investment, the thermal rating of the line and the surge impedance loading of the line (which is a function of the line's impedance). Each will be dealt with in turn. The value of the factors obtained is then translated into a score out of 10 with the present practice or normal standard being given a score of three.

Term 1 Life cycle cost in present day currency value (LCC).

This is one of the main aspects of line design and covers the determination of the optimum aluminium area required (the higher the aluminium area the lower the losses but the higher the capital cost), the maintenance costs, the operating costs, and project costs. Depending on the cost of capital and the cost of losses the solution may differ. For example, with a high cost of capital and low cost of losses the option with the smaller conductor area will likely to be the best.

The cost of losses must be determined using the integrated network losses, and not the losses relating only to the line itself. This is because it may be found that to include a line of low impedance in the integrated network may cause a power flow that increases the overall system losses.

The lower the number the better the score.

Term 2 Investment in capital in present day currency (IC)/MVA thermal

The second factor is a combination of the capital investment as well as the thermal rating of the line. The MVA thermal is referred to the power capability from the thermal viewpoint of the line. The higher the templating temperature the higher the thermal transfer capacity of the line and higher the capital cost. In reviewing the nature of the factor or parameter the optimum design is one that will have the highest thermal rating for the lowest cost. Thus in using a ratio the lower the value the higher the score. The absolute value of the ratio or the score is not important as the indicator is used for comparison of different designs.

The lower the value the better the score.

Term 3 Investment in capital present day currency (IC)/MVA surge impedance loading (SIL)

The MVA (surge impedance loading) is a function of the impedance of the line. Lower impedance may result in higher capital costs but not necessarily so. Certain compact or large bundle configuration lines providing lower impedance may prove a lower cost than the higher impedance lines. In order to combine the parameters of cost and power transfer capability a ratio as described as term 3 is proposed.. The lower the value the higher the score. The optimum line being the one with the lowest investment for the highest surge impedance loading.

The lower the value the better the score.

Stephen [2004] uses the line characteristics and costs to form ratios as per the terms defined above. The terms are combined in the following equation.

The equation according to Stephen [2004] is as follows:

$$ATI_{AC} = w_1 LCC + w_2 \frac{IC}{MVA_{sil}} + w_3 \frac{IC}{MVA_{th}} \qquad [6.1]$$

Where ATI_{AC} is the appropriate Technology Index (for AC).

LCC is life cycle cost using system losses, maintenance and initial cost

IC is the initial cost (Capital Investment) of the line

MVA_{SIL} is the surge impedance loading

MVA_{Th} is the thermal limit under contingency conditions

w is the weighting of the term

As the units of each term in the equation are different, the model proposes that the "objective matrix" method is used whereby the present line design standard is given a score of $^{3}/_{10}$. The score of $^{0}/_{10}$ or $^{10}/_{10}$ is arbitrary determined based on best estimate as to the best possible performance. The terms are then converted to scores out of 10 by using linear interpolation. The ATI_{AC} then results in a score out of 10 for a particular line design. The weighting of each term is determined by the network planners which will then determine the importance of each component in relation to the need of the line in the network. The LCC would be given a high rating if the cost of Capital relatively low and the marginal cost of generation is high. If the Cost of Capital (COC) is high the initial cost is often more important in relation to deciding whether the line is to be a "go" project or not. The lower the LCC is more effective the line design.

The MVA_{SIL} is an important factor for long lines (above 50kms) where the line will not be thermally limited but more limited due to system stability. The higher the MVA_{SIL} the higher the initial cost thus as a ratio the higher the ratio the more effective the line design.

The MVA_{Th} is an important factor on shorter lines that need to transfer large amounts of power under contingency conditions to ensure a reliable network.

Note that it may be argued that MVA_{SIL} is a more important factor than MVA_{TH} for the majority of lines above 132kV due to their being stability limited. The indicator does not assume that all factors are identical but allows for terms to be weighted in accordance with the priorities of the planner. The line design options considered also need to be able to meet the planners requirements as determined by load flow studies. All design options are therefore technically viable. This makes the need for an objective indicator more prevalent in that it may be difficult to determine the best set of options via intuition alone.

6.3. PROS AND CONS OF DIFFERENT INDICATORS

6.3.1 Life Cycle Cost

The life cycle cost has the following benefits:

1. The comparison is in monetary (rand) values which is easier to interpret.
2. The investment choice can be linked to benefit in currency.
3. There are no weighting factors that can obscure the choice.

The following are the cons for the indicator:

1. The LCC is a measure that does not cover other aspects of the line design, such as the use of the line in the network in relation to the SIL and the thermal rating.
2. The link to the planners requirements such as SIL or thermal rating is not measured.
3. The optimal LCC may result in a higher initial cost and larger cross sectional area of the aluminium than may be absolutely required by the network planners.

6.3.2 Composite Indicator

The composite indicator [Stephen, 2004] has the following benefits:

1. The factors, such as SIL and MVA (thermal) are included,
2. The weighting factors can be altered to determine the planners or utilities requirements. Thus LCC only can be used (making the indicator the same as that described by Vajeth [2004], or a combination of LCC and a measure of "bang for buck" in relation to MVA thermal and SIL.

The composite indicator has the following cons:

1. The measure is in a dimensionless point form which may prove difficult to describe to management committees.

2. The score derived is relative and not absolute. It is thus difficult to explain to decision makers that the line design is optimum because it has a score of 5/10 or 8/10 whereas management would be more concerned with the cost of the project and tend to go for the lowest initial cost which would result in the quickest payback period

3. When designing lower voltage lines on which the power transfer is limited by voltage drop, the MVA_{SIL} and MVA_{Th} parameters may not adequately describe the purpose of the line in the network.

4. The implementation of the weighting factors are problematic in that the future loading of the line is often very difficult to determine. One use of the weighting was that, by using a range of weightings, the most robust line design option can be determined.

6.3.3 Application Of The Indicators

In the use of the LCC method, the Table 6.1 indicates the ranking of the options in line with this method.

Case	Conductor bundles	Capital investment cost (USDm)	Life cycle benefit from reduced system losses (USDm)	Cost to make up additional power with shunts (USDm)	Overall life cycle cost (USDm)	Position	Deviation from best option (%)
1	3 x Tern	-38.57	150.71	-1.29	110.86	3rd	3.4
2	4 x Kingbird	-39.00	153.86	0.00	114.86	1st	0.0
3	2 x Bersfort	-38.71	149.29	-0.57	109.86	5th	4.3
4	3 x Greely	-43.29	154.29	-0.43	110.71	4th	3.6
6	2 x IEC-800	-40.71	151.14	-0.57	109.71	6th	4.4
7	4 x Tern	-48.14	157.14	-0.29	108.71	7th	5.4
8	3 x Bluejay	-44.43	156.43	0.00	112.00	2nd	2.5
11	3 x Bersfort	-53.86	158.86	-0.29	104.71	8th	8.8

TABLE 6.1 Life Cycle Cost With Additional Compensation Cost Added

The composite indicator results are shown below:

ATI Calculation Case	W1,W2,W3: 0.8,0.1,0.1	Rank	W1,W2,W3: 0.6,0.2,0.2	Rank	W1,W2,W3: 0.4,0.3,0.3	Rank	W1,W2,W3:0 .2,0.4,0.4	Rank	Average Rank
1.(3 x Tern)	3.84	4.00	3.82	2.00	3.80	2.00	3.78	3.00	2.75
2. (4 x Kingbird)	4.10	1.00	4.24	1.00	4.37	1.00	4.51	1.00	1.00
3. (2 x Bersfort)	3.88	2.00	3.71	3.00	3.53	6.00	3.36	7.00	4.50
4. (3 x Greely)	3.64	6.00	3.62	6.00	3.60	5.00	3.58	5.00	5.50
5. (6 x Pelican)	3.19	8.00	3.43	8.00	3.66	3.00	3.90	2.00	5.25
6. (2 x IEC-800)	3.86	3.00	3.66	5.00	3.46	8.00	3.26	9.00	6.25
7. (4 x Tern)	3.37	7.00	3.44	7.00	3.50	7.00	3.57	6.00	6.75
8. (3 x Bluejay)	3.73	5.00	3.69	4.00	3.65	4.00	3.61	4.00	4.25
9. (4 x Greely)	2.44	11.00	2.52	11.00	2.60	11.00	2.68	11.00	11.00
10, (6 x Kingbird)	2.46	10.00	2.73	10.00	3.00	9.00	3.27	8.00	9.25
11.(3 x Bersfort)	3.00	9.00	3.00	9.00	3.00	10.00	3.00	10.00	9.50
12.(4 x Bluejay)	2.25	12.00	2.35	12.00	2.44	12.00	2.53	12.00	12.00
13. (3 x IEC-800)	2.21	13.00	2.19	13.00	2.17	13.00	2.16	13.00	13.00

TABLE 6.2 Composite Indicator [Stephen, 2004] Rankings

The LCC method only looks at the first column in the Table 6.2. The rankings indicate that the other factors will bring in different options, in fact a number of options that are dropped in the LCC analysis will come to the fore when the SIL and MVA thermal is taken into account.

6.4. ANALYSIS OF DESIGNS

The LCC [Vajeth, 2004] method uses compensation to indicate the variation in the SIL of the design options. This is shown in the capacitance to be used to ensure the power transfer capability is comparable across all options. However, it could be argued that it is not realistic to add costs to the LCC which may not be required or ever installed. Thus, the composite indicator, in using the actual SIL of the lines seems to indicate a more equitable method of comparing designs.

The analyses of the designs in this case are as follows:

Both indicators show the quad Kingbird as the best option, however, the option 2 is shown as the 3 Bluejay conductors in the Vajeth [2004] method and 3 Tern in the composite indicator method. This is because the 3 Tern option displays excellent properties in relation to higher weighting in SIL and thermal rating. The life cycle cost is slightly higher than the other options hence its lower rating in the LCC method.

The composite method shows the most robust design based on the "bang for the buck" principal as it uses the ratio of initial cost to the MVA rating in terms of thermal rating and surge impedance loading. The robustness of the design can be determined from the ranking of the design in using various weightings. Thus if the design is high in ranking for a variety of weightings, it indicates that the "bang for the buck" components as well as the LCC are favourable for this design option. In this case the quad kingbird conductor is the favoured option which may be discounted due to the difficulty in construction and the reliability aspects.

6.5. INCLUSION OF THE CONSTRUCTIBILTY AND RELIABILITY FACTORS IN THE INDICATOR

Based on the discussion in chapter 5 it is feasible to include the reliability and constructability factors in the composite indicator. As the indicator described by Vajeth [2004] uses the LCC cost, it is likely that this indicator can include only the increase in the mitigation costs in the initial cost of the line. This is minimal in the case of the cost/km of an EHV line and is not likely to affect the outcome in terms of the LCC cost of the line as described by Vajeth [2004].

6.5.1 Inclusion Of Reliability In The Composite Indicator

As mentioned above, not all constructability and reliability functions can or should be included in the indicator. The composite indicator as described by Stephen [2004] is comprised of a number of factors that are scored out of 10 based on the present design being given a value of 3/10. The different components can thus be added together as they are dimensionless. The sum of the weightings need to total unity. Thus, this indicator can be readily modified to include the additional parameters.

In determining what to add in the indicator to include reliability and constructability, it is necessary to look at the factors that make up reliability and constructability. In the previous section it was mentioned that the reliability levels need to be determined as well as the environmental constraints, thus, it may not be necessary to include these aspects into the indicator. The main issue is the diameter to weight ratio as well as the number of conductors in the bundle which affects both constructability and reliability.

The ratio can either be included in the indicator or be used as a “gate keeper”. This implies that if the design is outside the ratio specified the design is not considered and therefore, does not obtain a score in the indicator for further consideration.

6.5.2 Inclusion Of Constructability

The constructability was not included in any of the indicators discussed; however, it is possible to include this aspect as a function of tower type or terrain route. Again this is likely to be subjective and vary from contractor to contractor.

The contractors practiced in certain tower type may find that tower type easier to construct than others. This is more a reflection of their ability rather than the construction parameters of the tower type itself.

Thus, it depends on the line, terrain, contractor and equipment available at the time in determining the constructability of the line. With this complexity it is considered preferable to discuss this aspect with the stakeholders for the optimum group of designs identified by the indicator.

6.6. USE OF INDICATORS FOR DIFFERENT TOWERS AND PHASE SPACING

The example used previously on the 400 kV line in the Eastern Cape Province in South Africa, used the same tower series with different conductor types. It is necessary to check the robustness of the indicators with different towers and phase spacing.

6.6.1 Example "Camden Duhva" 400 kV Line

The indicators were used to evaluate options on the "Camden Duhva" 400 kV line over 105 km in the Mpumalanga Province in South Africa. The line is linking two very strong supply points and stability is not a limiting factor.

In this particular example it was decided to set limits for the 0 and 10 scores to enable simple analysis of different projects. Thus the Quad "Zebra" (present solution) is not always 3/10 in Table 6.3.

Using this as approximately 3 the 0 and 10 levels for the three factors are as follows:

k_1 0 = 125 000 (units of currency)

10 = 60 000 (units of currency)

k_2 0 = 2.5 (units of currency/ km/ $MVA_{thermal}$)

10 = 1.0 (units of currency/ km / $MVA_{thermal}$)

k_3 0 = 9 (units of currency/ km / MVA_{sil})

10 = 4 (units of currency/ km / MVA_{sil})

The scores are non-dimensional entities.

Once the scores have been obtained for the different design options the factors are combined using weighting factors i.e.

Appropriate Technology Index (ATI) = $w_1k_1 + w_2k_2 + w_3k_3$ [6.2]

These weighting factors would depend on the line in question. In a very tight system, such as is the case with the “Camden Duhva” line the SIL (surge impedance loading) weighting may not be as important as the thermal rating. In a long radial feeds the reverse may be true. Although it may be said that these weighting factors may be extremely difficult to determine, results show that one or more tower and conductor options will indicate consistently good performance over a range of weighting factors.

Case	Al area mm^2	Description	K_1 (LCC)	K_2 (IC/MVA_{th})	K_3 (IC/MVA_{SIL})
1	1715	4XZebra V	103,53 [3,30]	28,13 [3,07]	7,43 [3,19]
2	1817	3XBunting V	84,4 [6,25]	19.48 [5,20]	6,31 [5,38]
3	2423	4XBuntingCRS 6.5m	88,36 [5,64]	13.27 [6,73]	7,02 [3,96]
4	1935	4XRail CRS 6.5m	87,76 [5,73]	14.32 [6,47]	5,94 [6,12]
5	1933	3xBittern CRS 6.5m	82,91 [6,48]	17.86 [5,60]	6,31 [5,38]
6	2901	4XBoblink CRS 6.5m	93,33 [4,87]	17.04 [5,80	8,06 [1,88]
7	2059	3xBersfort CRS 8.2m	80,41 [6,81]	16.23 [6,00]	6,30 [5,40]

Table 6.3 Showing examples of the terms k_1 to k_3 scores shown in brackets.

Table 6.3 shows the calculated factors that are used to make up the ATI. The options referred to are:

1. Quad “Zebra” (428 A1S1A 54/7 Zebra) (where 428 refers to the aluminium area in mm^2, A1S1A refers to the type of aluminium and steel, 54/7 refers to the strands of aluminium and the strands of steel and Zebra refers to the code name of the conductor). guyed Vee tower
2. Triple “Bunting” (605 A1S1A 45/7 Bunting) conductor guyed Vee tower.

3. Quad “Bunting” (605 A1S1A 45/7 Bunting)cross rope suspension (CRS) tower with a phase spacing of 6,5m.

4. Quad “Rail” (484 A1S1A 45/7 Rail) conductor with a CRS tower with a 6,5m phase spacing.

5. Triple “Bittern” (644 A1 S1A 45/7 Bittern) conductor with a CRS tower with a 6,5m phase spacing.

6. Quad “Boblink” (725 A1S1A 45/7 Boblink)conductor with a CRS tower with a 6,5m phase spacing.

7. Triple “Bersfort” (687 A1S1A 48/7 Bersfort) conductor with a CRS tower with a 8,2m phase spacing.

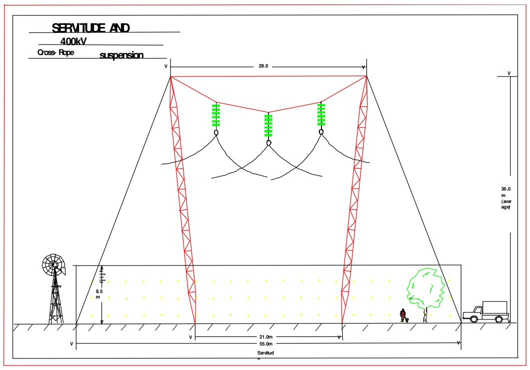


Figure 6.1 Cross Rope Suspension Tower (Variable Phase Spacing).

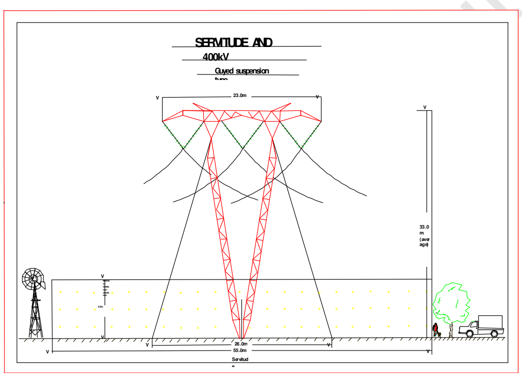


Figure 6.2 Guyed Vee Tower (Type 518).

The Figure 6.1 shows the schematic of the cross rope suspension tower (CRS) Figure 6.2 as well as the guyed vee tower. It should be noted that the CRS tower does not have a tower “window” and hence the phase spacing can be varied from 8,2 m (standard for 400 kV on the guyed vee tower) and 6,5 m (compact design).

The scores out of 10 in Table 6.3 are shown in square brackets. From the Table 6.2 it is not possible to determine the best option. It is necessary to determine the value of the combination of factors using the ATI_{AC}. The results are shown in Table 6.4

Case	$w_1;w_2;w_3$	$w_1;w_2;w_3$	$w_1;w_2;w_3$	$w_1;w_2;w_3$
	0,8;0,1;0,1	0,6;0,2;0,2	0,4;0,3;0,3	0,2;0,4;0,4
1	2,82 [7]	2,89 [7]	2,96 [7]	3,03 [7]
2	5,80 [3]	5,67 [4]	5,55 [4]	5,42 [4]
3	5,23 [5]	5,18 [5]	5,14 [5]	5,09 [5]
4	5,56 [4]	5,74 [3]	5,93 [2]	6,11 [1]
5	6,04 [2]	5,90 [2]	5,77 [3]	5,63 [3]
6	4,33 [6]	4,21 [6]	4,08 [6]	3,96 [6]
7	6,42 [1]	6,24 [1]	6,06 [1]	5,88 [2]

Table 6.4 Indication Of The Ranking Of The Cases.

6.7. DISCUSSION OF THE RESULTS

It should be noted that the ATI_{AC} is a guide and provides for areas of further investigation rather than absolute answers.

In Table 6.4 the ranking of the options are shown in [] brackets. The lower the number the higher the rank.

It can be noted from the Table 6.4 that the present day option, which was considered the best before use of the ATI_{AC}, is ranked last for all weighting options.

From the results dealing with the "Camden Duhva line" it is apparent that the option 7 (3xBersfort conductor on the Cross Rope Suspension tower with a phase spacing of 8.2m) should be used if LCC criterion is dominant. Option 4 (4xRail on the CRS tower) should be used if thermal rating or surge impedance is the overriding factor.

The results highlight the benefit of the CRS tower both from lower steel content as well as the ability to compact the phases. The tower has a more marked effect on the cost of the support steel than the conductor core.

From the findings, it is necessary to discuss once again with the planners as to the best option to adopt. In this case, the thermal and SIL rating was not more important than the life cycle cost. Option 7 was therefore the option adopted.

The "Camden Duhva" line was evaluated separately from the ATI_{AC} initially. The results without using the ATI_{AC} and using it were identical. This gives confidence in the validity of the solutions highlighted.

6.7.1 Use Of The LCC As An Indicator

The Table 6.4 column 1 indicates the LCC option and indicates, in this case that the option 7 may be the best option. However, it does not include the other parameters which cater for the SIL or the MVA transfer capability. It is thus a more superficial indicator and will not indicate the robustness of the particular design to different planning requirements, such as thermal rating or SIL. It also does not indicate the "bang for the buck" as the indicator as described by Stephen [Stephen 2004] tends to do as it uses ratios of the power transfer and SIL to initial cost.

6.8. DEVELOPMENT OF AN AC INDICATOR

Based on the above analysis it is possible to determine a representative indicator for AC lines.

It is shown that to use the LCC method by Vajeth [2004] is not conclusive as it does not include other parameters, such as MVA thermal rating or the ratio of MVA obtained for the amount of funds invested.

The other drawback is that Vajeth [2004] includes capacitor banks as a means to quantify the differences in power flow in rand terms in order to compare the design options. However, if the reactive compensation is not planned to be installed, the wrong option may be considered.

A positive aspect of the work of Vajeth [2004] is that the actual load flow is conducted to determine the losses of the line in the network. This can also be used to determine the MVA transfer as a result of voltage and stability constraints.

The indicator proposed by Stephen [2004] proposes that load flow studies are used to determine the LCC portion of the indicator as is the case with Vajeth [2004], however, the MVA (thermal) and MVA (SIL) values are calculated values and are not the values that can be transferred down the line. This is determined by network configuration which determines limits of transfer due to voltage or stability constraints.

The voltage drop criteria is not specifically included in any of the indicators studies but is implicitly included in the fact that there are load flow studies undertaken for both of the indicators. Thus, it could be argued that if load flow studies are undertaken the voltage and stability limits are taken into account in that if the line design option is not suitable as a result of these constraints, it will not be considered for further analysis.

6.8.1 VARIATION OF PLANNERS REQUIREMENTS

As mentioned in section 6.7, the planner’s requirements are not always well defined. Location of Generation plant, load variations, and future network layout are often not known exactly at the time of design. Thus it is important that the indicator is robust so that it can cater for a number of parameters required by the planner in terms of SIL, thermal rating and LCC. It is also important that the planners are involved in the design process to ensure that the final design will meet their requirements.

6.8.2 CASE FOR INNOVATION

Although the indicator is by no means a method by which the line design can be fully optimised as would be the case perhaps with an expert system, it is a means to assist the designers of different disciplines from testing their ideas against an objective measure from which a group of favourable designs can be taken further to the detailed design stage.

The indicator also links the design options to the needs of the network planner and measures the "bang for the buck" or benefits as a function of unit cost.

With reference to the literature survey there is no are very few such methods that link the planner's needs to the line design and is able to objectively quantify the effect of different design options.

6.8.2 CONCLUSION

The following conclusion can be reached:

- The indicator's parameters must be determined by actual load flow studies as well as calculated R, X and B values. The load flow analysis needs to take into account the various contingencies from a network and generation viewpoint.
- The voltage drop, stability limitations, as well as the reliability criteria in terms of the weight to diameter ratios needs to be used as a "gate keeper" for the line design options that are to be further analysed.
- The ratios proposed by Stephen [2004] which indicate the amount of power transfer from a thermal and SIL viewpoint (based on calculation not load flows) as a function of currency invested gives an idea of the benefit of the design option. Thus with the load flow analysis and the calculated values the indicator proposed by Stephen [2004] can indicate the most efficient investment in terms of initial capital invested.
- The example shown for the "Camden Duhva" line does not strictly put the value of the present solution at 3.00. Although the results may be identical if there are designs very close to the present design it may be difficult to determine which of the options are assumed as the present design. It is proposed, therefore, that the present design options are given a value of exactly 3.0.

6.9. RECOMMENDED INDICATOR FOR AC LINES.

The recommended indicator for AC lines is therefore that proposed by Stephen [2004] however, with the following additions:

- That the load flow analysis be undertaken to determine losses as well as those design options that will not be voltage or stability limited.
- The reliability criteria for weight to diameter ratio be included as a "gate keeper"

- The ratios be used as indicated by Stephen [2004]
- The current option be given a score of 3 and the linear function be determined per case rather than the generic limits as shown in the "Camden Duhva" case study.

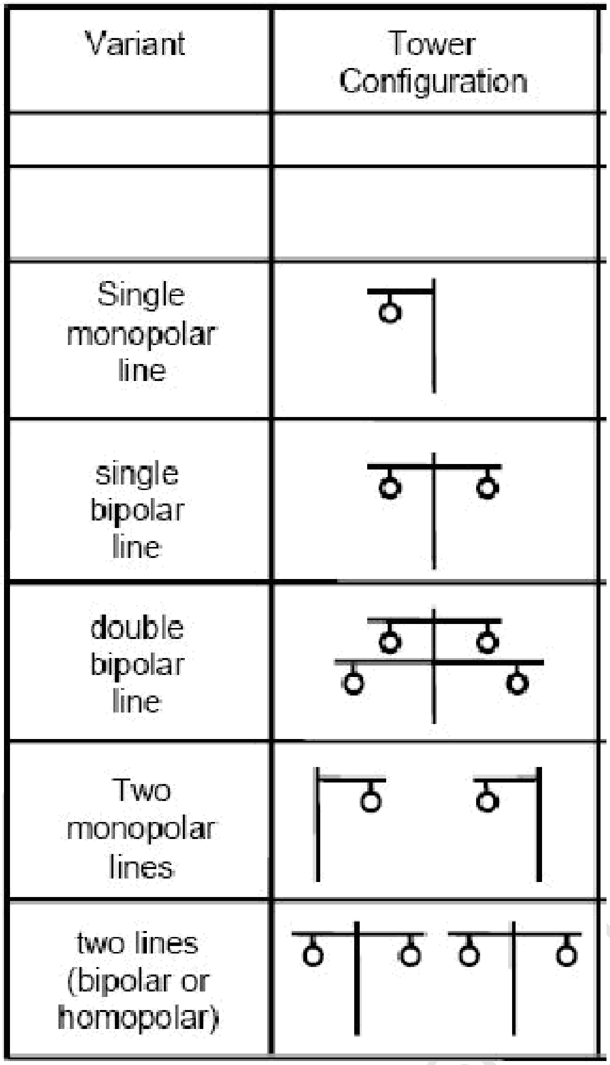
CHAPTER 7

DC PARAMETERS

7.1. INTRODUCTION

As with AC lines (section 3.1), the DC line is a device that transmits power over long distances [Stephen, 2004]. With HVDC lines the line is often a point to point supply over long distances. In this case the terminal equipment and line design can be tailor made to the load transfer capability required.

Whilst the mechanical aspects of both AC and DC lines are similar, the DC line can have 1 or 2 poles per structure. The electrical parameters are very different. The various types of DC configuration are shown below [Nolasco, 2009].



Variant	Tower Configuration
Single monopolar line	
single bipolar line	
double bipolar line	
Two monopolar lines	
two lines (bipolar or homopolar)	

Figure 7.1 Different DC configurations

The HVDC options are shown in figure 7.1 and indicate a wide variety of conductor locations on tower types for bipolar and monopolar designs. In addition each tower can be guyed or self supporting adding more variation.

7.2. LOAD FLOW CHARACTERISTICS

The load flow on DC lines is determined merely based on the V=IR ohms law. The maximum power flow is a function of the permissible volt drop and the line length. This is shown below [Singh, 2005].

$$P_{\max} = \frac{V^2}{10R_x L} \qquad [7.1]$$

for 10% volt drop and

$$P_{\max} = \frac{V^2}{\sqrt{44}R_x L} \qquad [7.2]$$

for 15% volt drop where

Eq [7.2] is only an approximation of the actual. The proper calculation would be

$$P_{\max} = \frac{V^2 \times vd\%}{100R_x L} \qquad [7.3]$$

where vd% is the voltage drop expressed as a % of V,

and the equation applies for both 10% and 15% volt drop. {1/sqrt(44) is an approximation of 15/100} and the format removes the generality of the basic and simple equation.

V=Sending end voltage, pole to ground in kV

R_x=DC Resistance of the conductor in ohm/km

L=Distance in kilometres.

Thus, with a higher sending end voltage, lower resistance and shorter distance the power flow can be increased. As there is limited means to adjust the distance the designer has the option of sending end voltage, voltage drop that is allowable, and resistance.

7.3. CALCULATION OF DC RESISTANCE

The calculation of DC resistance is a function of the construction of the conductor and is described in Stephen [1992]. The formulae basically calculate the resistance per strand and determine the total resistance as a parallel combination of the individual wire resistances.

Conductance of steel core (if present):

$$\frac{1}{R_s} = \frac{\pi d_s^2}{4\rho_s}\left[1 + \sum_{1}^{n_s} \frac{6 z_s}{K_{sz}}\right] \qquad [7.4]$$

where

$$K_{sz} = \sqrt{1 + \left(\frac{\pi d_{sz}}{l_{sz}}\right)^2} \qquad [7.5]$$

d_s = diameter of steel wire

ρ_s = resistivity of steel at 20°C

z_s = layer number of steel wires

d_{sz} = mean diameter of layer z

l_{sz} = lay length of layer z

n_s = number of layers of steel wires

The conductance of each non-ferrous layer:

$$\frac{1}{R_{az}} = \frac{\pi\, d_a^2 n_{az}}{4\rho_a K_{az}} \qquad [7.6]$$

where

$$K_{az} = \sqrt{1+\left(\frac{\pi\, d_{az}}{l_{az}}\right)^2} \qquad [7.7]$$

d_a = diameter of non-ferrous wire

ρ_a = resistivity of non-ferrous material at 20°C

d_{az} = mean diameter of layer z

n_{az} = number of non-ferrous strands in layer *z*

l_{az} = lay length of layer *z*

n_a = number of layers of non-ferrous wires

The total resistance of the conductor is found from:

$$\frac{1}{R_{dc}} = \frac{1}{R_s} + \sum_{1}^{n_a} \frac{1}{R_{az}} \qquad [7.8]$$

Note that the parameters are determined at 20^{o}C and then the entire R_{dc} term is modified in terms of temperature in the steady state equation for determination of conductor temperature as found in Stephen [1992]

DC resistance is not a function of current as there is no transformer effect. The current may result in a temperature increase which then increases the resistance from the value stated in eqn [7.8] via the steady state equation listed in Stephen [1992].

7.3.1 Construction Of The Conductor

The conductors used on HVDC lines need not be any different from the conductors used for AC lines. The benefit of not having the transformer or skin effect does not penalise the steel core options and effect of lay ratios are more related to the dc resistance of the conductor and the resistance is therefore not a function of the current directly. Obviously as the resistance is a function of temperature and temperature is a function of current, the resistance is a function of current indirectly. In the case of the transformer and skin effect the resistance is a direct function of current irrespective of temperature.

7.4. CORONA INCEPTION GRADIENT

According to Maruvada [2000] the corona inception gradient for negative corona (note that negative corona inception gradient is lower then for the positive case and is usually about 90% of the positive case) is given as follows:

$$E_c = 30m\delta\left[1 + \frac{0.308}{\sqrt{r\delta}}\right] \text{ kV/cm} \qquad [7.9]$$

m = is the surface roughness factor, and typically lies between 0.7 and 0.9 for a stranded conductor. For an ideal smooth conductor, m=1. This is the same factor for DC and AC.

r = radius of conductor in cm

δ = relative air density.

δ is given by equation as follows:

$$\delta = \frac{293p}{760(273+t)} \qquad [7.10]$$

where

p = prevailing atmospheric pressure in mm of mercury, where the reference pressure is 760mm. If kPa measures are used the reference pressure becomes 101.3kPa. The number 101.3 will then replace 760 in the equation.

t = is the ambient temperature in ^{o}C.

According to EPRI [1993] the E_{max} maximum conductor gradient, is calculated in a similar manner to the AC conductor gradient. The following equations [7.11] to [7.16] are all sourced from EPRI [1993].

$$E_{\max} = E_{ave}\left[1+\frac{d(n-1)}{D}\right] \qquad [7.11]$$

where

E_{max} is the maximum surface field gradient kV/cm

E_{ave} is the average surface field gradient kV/cm

d is the diameter of the subconductor in the bundle cm

D is the bundle diameter cm

n is the number of sub-conductors in the bundle

For bipolar lines with horizontal configurations E_{ave} can be expressed as follows:

$$E_{ave} = \frac{2V}{\left[nd \times \ln\left(\frac{T}{F}\right)\right]} \qquad [7.12]$$

where V is the voltage to ground, and F and T are coefficients dependent on the line geometry

$$F = \sqrt{1 + \left(\frac{2H}{P}\right)^2} \quad [7.13]$$

$$T = \frac{4H}{d_{eq}} \quad [7.14]$$

where

H is the average conductor height and P is the spacing between the positive and negative poles.

$$d_{eq} = D\left(\frac{nd}{D}\right)^{\frac{1}{n}} \quad [7.15]$$

where

D is the bundle diameter (cm), n is the number of sub-conductors in the bundle

d is the diameter of the sub-conductors (cm),. The bundle diameter is related to the spacing S between the sub-conductors

$$D = \frac{S}{\sin\left(\frac{\pi}{n}\right)} \quad [7.16]$$

As with AC parameters, the gradient is dependent on the size of the bundle and the pole spacing as well as height above the ground. The higher the conductor diameter and the more sub-conductors in the bundle the more resistant the bundle is to corona and therefore the designer is more able to raise the voltage to ground and hence increase the power capability of the line.

Table 7.I Singh [2005] indicates the different values of E_{max} and E_c the corona inception voltage calculated using EPRI TLW 3.0 software.

Cond	E_c	E_m n = 4 500 kV	E_m n = 5 500 kV	E_m n = 5 600 kV	E_m n = 3 800 kV	E_m n = 4 800 kV	E_m n = 5 800 kV
Bersfort	24.4		19.0			34.8*	30.4*
IEC800	24.3	20.8	18.2	21.9	35.3*		26.0*

Table 7.1 Corona Inception And Maximum Voltages. (4X Bersfort and 4X IEC 800) showing the surface field voltage for different cases. The * refers to cases which exceed the corona inception voltage

The conductors are ACSR Bersfort (686.5-A1S1A refer Appendix 1) overall diameter 35.56mm and IEC 800 (800-A1-S1A refer Appendix 1) overall diameter 37.6mm.

According to Singh [2005], in South Africa the ratio of allowable corona performance is $E_{max}/E_c<0.95$, where E_c is the corona inception gradient. For E_c=24.3kV/cm, E_{max}<23.08kV/cm.

From Table 7.1, the corona inception voltages for the Bersfort and IEC800 conductors are 24.4kV/cm and 24.3kv/cm respectively resulting in allowable E_{max} values of 23.18kV/cm and 23.08kV/cm respectively. The figures with asterisks indicate where the E_{max} as calculated exceeds the maximum allowable E_{max}. with the given height and conductor spacing.

As seen from the above equations the higher the number of sub-conductors in the bundle and the higher the subconductor diameter the lower the E_{max} for a constant voltage to ground.

7.5. CORONA POWER LOSS

In HVDC lines the loss of power due to corona on long lines is important. HVDC lines are also generally longer than AC lines thus the losses in total are greater. According to Singh [2005] the corona loss is given by the following formulae:

In fair weather

$$P = 2.9 + 50\log\left(\frac{E_{\max}}{25}\right) + 30\log\left(\frac{d}{3.05}\right) + 20\log\left(\frac{n}{3}\right) - 10\log\left(\frac{HS}{225}\right) \quad [7.17]$$

and foul weather

$$P = 11 + 40\log\left(\frac{E_{mas}}{25}\right) + 20\log\left(\frac{d}{3.05}\right) + 15\log\left(\frac{n}{3}\right) - 10\log\left(\frac{HS}{225}\right) \quad [7.18]$$

Where P is the corona loss is dB above 1 W/m, E_{max} is the positive polarity maximum bundle gradient in kV/cm, d is the sub-conductor diameter in cm, n is the number of sub-conductors in the bundle, H is the average conductor height in m and S is the pole spacing in m.

The equations have been drawn in the paper by Singh [2005] from Maruvada [2000] and are based on earlier work by Maruvada [1970], which states the following conclusions (based on analysis using the algorithms developed in the paper) quoted below:

"Monopolar Lines

1) *From the point of view of decreasing corona losses on monopolar lines, an increase in the height of the conductor has a much larger influence than an increase in its size.*
2) *A change in the conductor surface irregularity factor is equivalent to a similar change in the size of the conductor, i.e., an increase in the surface irregularity factor gives rise to a corona loss characteristic which is essentially similar to that obtained with a larger conductor, and vice versa.*
3) *An increase in the number of sub-conductors in a bundle with all the other line parameters remaining constant results in a decrease in corona losses similar to that caused by using an equivalent single conductor of larger size.*

4) *There is an indication that the exact location of sub-conductors with respect to ground has an influence upon the value of resultant corona loss.*

5) *An increase in the bundle spacing gives rise to higher corona losses because of the decrease in the relative proximity effect of the conductors.*

Monopolar Lines with Overhead Ground Wires

6) *An increase in the size of the ground wire mainly causes an increase in the voltage at which corona occurs on the ground wire. At the same time it also gives rise to a small decrease in the corona onset voltage on the conductor and consequently leads to somewhat larger corona losses.*

7) *The effect of increasing the height of the ground wire is to produce a considerable decrease in corona losses. In addition, the voltage at which the transition to the bipolar mode occurs is also somewhat increased."*

Based on the above conclusions it is apparent that the corona parameters are similar to those of AC as mentioned below:

- System voltage
- Conductor diameter
- Clearances between conductor and adjacent conductors
- Clearance between conductor and earth
- Number of conductors per pole
- Bundle geometry (diameter of bundle position of sub-conductors)
- Conductor surface condition
- Atmospheric and weather conditions
- Earthwire design and location

The DC corona is also a function of the ground wire size and height above ground (which is also the case for AC corona).

For reduced corona loss a lower E_{max} is required for a given voltage thus higher bundle diameters and more sub-conductors will be preferable.

7.5.1 Radio And Audible Noise

According to Maruvada [2000] the radio noise is calculated from

$$RI = 51.7 + 86\log\left(\frac{E_{max}}{25.6}\right) + 40\log\left(\frac{d}{4.62}\right) \qquad [7.19]$$

and audible noise is calculated as follows:

$$AN = AN_0 + 86\log(E_{max}) + k\log(n) + 40\log(d) - 11.4\log(R) \qquad [7.20]$$

Where E_{max} is the average maximum bundle gradient in kV/m, n is the number of sub-conductors, d is the conductor diameter in cm and R is the radial distance from the positive conductor (note that audible noise is a function of distance from the source as the magnitude decreases with distance whereas radio interference is more wide spread) to the point of observation in m (generally the servitude boundary) and

k = 25.6 for n>2

= 0 for n=1,2

AN_0=-100.62 for n>2

=93.4 for n=1,2

According to Singh [2005] “no limits exist (in all countries) for radio interference and audible noise for HVDC transmission lines, however, the line designs must be compatible with local radio and broadcast services as well as general electromagnetic environment”.

7.5.2 Summary

The corona losses as well as the AN and RI increase with E_{max}. E_{max} is a function of the pole spacing, and number of sub-conductors in the bundle, the higher the sub-conductors in the bundle the lower is the E_{max} for a given voltage. E_{max} is the maximum voltage gradient on the conductor.

7.6. MECHANICAL CONSIDERATIONS

The same relationships for AC apply to DC with regard to mechanical considerations. The fewer sub-conductors in the phase the lower the wind forces on the tower. The lower the UTS the lower the horizontal forces applied to the towers for a standard percentage every day tension and the wider the tower the lower the forces on the guy wires for guyed vee and cross rope suspension towers.

7.7. THERMAL RATING

The thermal rating calculation for DC rating is similar to AC with the exclusion of the magnetic heating. The steady state equation stated in the AC section (equation [3.25]) is thus still valid.

In the case of DC lines, the load factors are closer to unity than on AC lines as the power flow can be controlled. Thus it may be preferable to allow for higher templating temperatures to increase the power flow capability of the line which is, in this case, only voltage and temperature limited.

7.8. OTHER FACTORS

Other factors such as overvoltages, lightning performance, right of way (ROW) or servitude options will need to be taken into account for each line design to determine the ROW requirements depending on the tower types chosen. Guyed and cross rope towers will have a larger tower footing area than self-supporting but may have lower phase spacing thus reducing ROW requirements as far as conductor blow out is concerned. These are covered in detail in Nolasco [2009] with a guideline being given for clearances as shown in Table 7.2.

Voltage (kV)	n cond.	MCM*	Code	Operating Voltage Clearance (m)	Operating Voltage Swing Angle (°)	Switching surge Clearance to Tower (m)	Switching surge Clearance to Guy wires (m)	Switching surge Swing Angle (°)
±300	2	2,167	Kiwi	0.7	46.9	1.3	1.23	7
	4	1,780	Chukar	0.7	47.5	1.3	1.23	7.1
±500	2	1,272	Bittern	1.2	52	3.06	2.87	8.1
	3	1,590	Lapwing	1.2	49.5	3.06	2.87	7.5
	4	2,167	kiwi	1.2	46.9	3.06	2.87	7
±600	3	1,272	Bittern	1.5	52	4.14	3.89	8.1
	4	1,780	Chukar	1.5	47.5	4.14	3.89	7.1
	6	2,167	Kiwi	1.5	46.9	4.14	3.89	7
±800	6	954	Rail	1.9	55	6.81	6.37	8.8
	5	2,167	Kiwi	1.9	46.9	6.81	6.37	7

Table 7.2 Typical clearance values for various voltage and conductor /bundle options. [Nolasco,2009] 1MCM is 0.5067mm^2. (note: these conductors are American standard specified in MCM hence the conversion given)

The clearances and other factors are largely independent of the conductor/bundle (assuming the options are reliable and do not have the diameter/weight ratio as mentioned in Chapter 5) and more linked to the voltage level. Thus, in the optimisation of the line using a specific voltage level, these factors are common to all options.

7.9. CONCLUSION

The corona limitations in relation to loss, E_c and E_{max} are the important parameters with regard to DC transmission lines. Thus the bundle design and the positive and negative pole separation as well as the voltage chosen for the optimal power flow is critical in the optimisation of the HVDC lines.

The table below summarises the options relating to conductor and bundle selection for HVDC lines. Note that the SIL mentioned in the AC section is not valid for HVDC. Hence, this column is replaced with voltage drop. Where

"Bad" implies that the option chosen will require that parameter to be studied in depth and mitigation action taken.

"Good" means that the parameter will be favourably influenced by action (e.g. the voltage drop will be lower with large Al area conductors).

"Neutral" means that the parameter chosen will not be affected by the choice of action.

Action	Parameter	Voltage drop	Corona	Mechanical loading	Thermal rating
+ and - pole spacing decrease		Neutral	Bad	Good	Neutral
Large Al area/cond (less conductors)		Good	Bad	Good	Bad
Diameter bundle increase		Neutral	Bad	Bad	Neutral
High steel content		Neutral	Neutral	Bad	Good

Table 7.3 Relationship between actions taken in line design and effect on voltage drop, Corona, Mechanical loading and thermal rating

It is apparent that for low corona and corona loss, the requirement is for a high number of sub-conductors in the bundle with low overall bundle diameters and high pole spacing. Note that in this case the decrease in pole spacing refers to a bipolar line which is good from a mechanical viewpoint. This is because of the forces imposed on the tower due to a broken conductor condition are less if the moment on the tower is less. The spacing between two separate monopolar lines will have no effect on the mechanical characteristics.

CHAPTER 8

OPTIMISING HVDC LINE DESIGN

8.1. INTRODUCTION

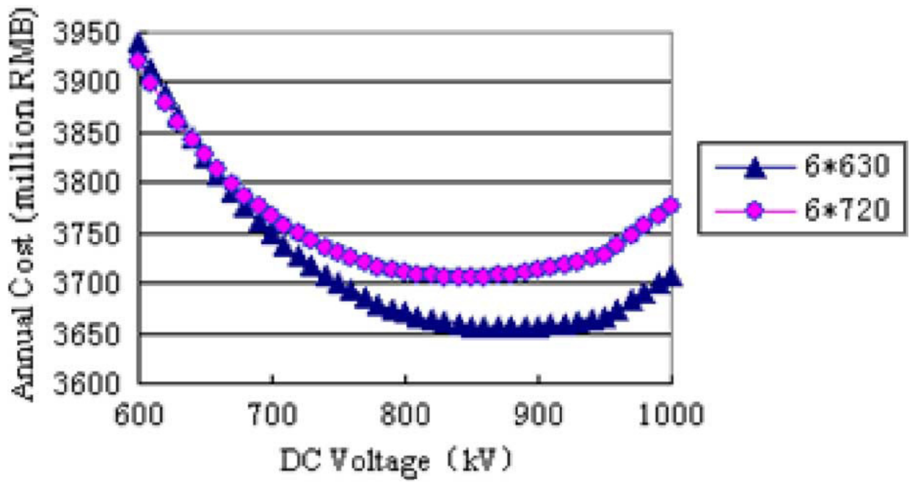
The HVDC line design exhibits more system parameters than the AC line. In the case with AC, the voltage is generally fixed as are the start and end points of the line. In the case of DC the voltage is a function of the optimisation process and is normally a function of the acceptable voltage drop, power transfer requirements, and length of line.

8.2. VOLTAGE AND CONDUCTOR BUNDLE SELECTION

8.2.1 Voltage Selection And Conductor Bundle Selection

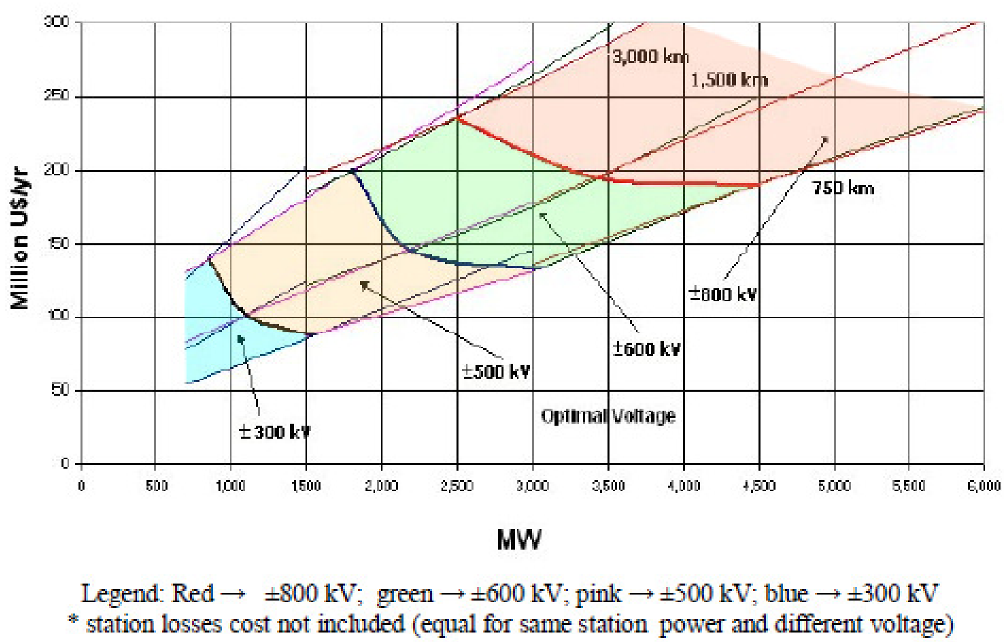
In this process the voltage for a given power requirement and line length, a selection of voltages, and conductor choices are made for voltage drops of 10 and 15%. The paper by Singh [2005] does not, however, look at the cost of the terminal equipment in increasing the voltages from 500 kV to 800 kV and concentrates on the line optimisation.

Jinhua [2009] uses a different approach whereby the voltage is determined using economics of the different types of terminal stations (different HVDC switching and valve configurations) as well as interest rates and generation costs per project. A graph, shown below (graph 8.1) is then developed per project indicating the optimum voltage level for two conductor/bundle types (these are 6 conductors in one bundle with each conductor being 630mm^2 and another case with 6 conductors in a bundle with each conductor being 720mm^2. The cost is an annual cost taking into account the converter and line losses (joule and corona) as well as the annual payment of capital. Of interest is that the smaller conductor is the lower cost for a large range of voltages. Thus the corona limitations will determine the smallest subconductor diameter bundle .that can be used for the particular voltage level. In the case of graph 8.1 it is possible that the 6X630 mm^2 will not be suitable from a corona point of view above 850 kV (this will have to be checked).



Graph 8.1: Annual cost as a function of DC voltage and conductor/bundle type [Jinhau, 2009]

A far more comprehensive analysis of costs is to be found in Nolasco [2009] where a detailed analysis of a range of line configurations, voltages, and terminal station options are taken into account. The following results are obtained from this document which will allow for a designer to rapidly determine the voltage level for a particular load and line length. From this graph it is possible to determine the optimum voltage for a particular load and distance as a function of annual cost per year. The cost is a function of the losses as well as the payment of the initial capital invested.



Graph 8.2 Optimal Voltage As A Function Of Converter Station Power And Line Length [Nolasco, 2009]

A combination of the two approaches is most probably the optimum way to optimise the HVDC line. The approach used by Jinhau [2009] or preferably by Nolasco [2009] should be used initially by the utility to determine the ideal voltage range for a particular project. After that is determined, the optimum conductor/bundle as well as tower and foundation combination is chosen.

As this thesis is to objectively determine the best line design, the voltage should be determined prior to the line being optimised. As mentioned in 1.8 the indicator proposed does not take into account voltage variation in AC or DC. This is because there will be too many variables to objectively determine the best option. The voltage needs to be determined prior to the line designs being determined

The voltage drop approach used by Singh [2005] is not backed up by economic analysis and thus is superficial for illustrative purposes only. Thus as a source this data and method is not supported. The voltage drop will be taken into account in the cost analysis as covered by Jinhau [2009] as well as by Nolasco [2009] as the more relevant source.

8.2.2 Calculation Of Corona

The next step is to determine the E_c and E_{max} values to determine, for the given voltage, the conductor/bundle configurations that are valid.

Following this certain conductor bundle combinations may be disqualified due to the E_{max} exceeding the E_c values.

The corona power loss is then calculated per valid conductor/bundle options.

8.2.3 Calculation Of Life Cycle Costs For Voltage Level Determination

Singh [2005] calculates the life cycle cost of the line using the initial cost as well as cost of losses, both power and corona loss for the conductor/bundle configurations and the voltage drops of 10 and 15%.

The yearly cost is the line investment and losses as well as station cost.

In the graph 8.2 above, three set of line length are indicated namely 750 km, 1500 km and 3000 km for each length a set of curves of the costs for the voltages alternatives are indicated. From these the boundaries of changing optimal voltage is identified. For example, for 1500 km with power transfer below 3500 MW the voltage ±600 kV is the most economic whereas above this level ±800 kV is preferred. [Nolasco, 2009]

Using these curves the example given by Singh [2005] of 4000 MW over a distance of 3500 km would indicate that the ±800 kV level is almost insufficient and would exclude the option of looking at lower voltages.

The example used by Jinhau [2009] of 6333 MW over 2133 km would similarly indicate that ±800 kV may be insufficient which is borne out by his analysis indicating ±850 kV may be more suitable.

Thus, using the work of Nolasco [2009] or Jinhau [2009] it is possible to obtain a fair idea of the ideal voltage for the length and power required. This analysis is based on present converter station costs although it is interesting to note that the voltage for the Cahora Bassa line in South Africa (built in 1975), is appropriate according to work done by [Nolasco].

8.3. PROPOSED PROCESS FOR OPTIMISATION OF HVDC LINES

Based on the work by Jinhau [2009], Singh [2005] and Nolasco [2009], the following optimisation process can be considered for a given power transfer and line length requirement.

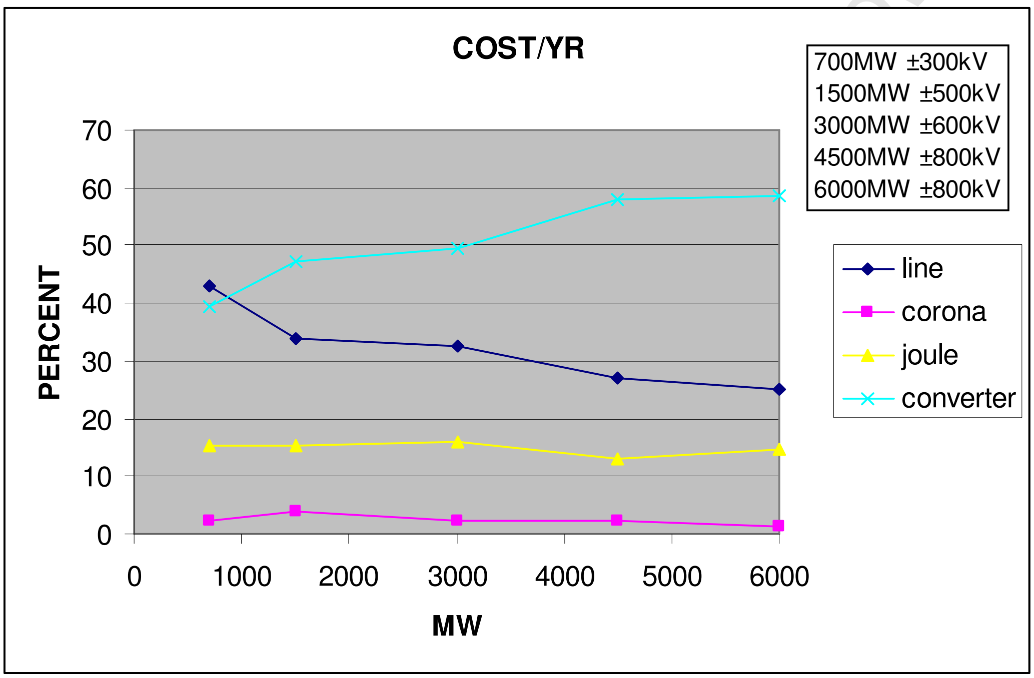
8.3.1 Decide On Optimal Voltage

From the curves of Nolasco [2009] or using the more detailed method proposed by Jinhau [2009], the voltage level can be decided. There should therefore be no need to design lines for different voltage levels.

8.3.2 Decide On The Conductor/Bundle Configurations.

The power loss is the major factor in the running of the line and based on the initial cost, the total cost of the line, including losses, can be determined for a number of conductor/bundle configurations that will meet the corona requirements of the voltage chosen.

The following graph from Nolasco [2009] indicates the percentage of costs for different voltages for a given power transfer.



Graph 8.3 Cost Parcels In % Of Total For Each Case (1500 km Line) [Nolasco, 2009]

Of note in the above graph is that the corona power losses are relatively low in cost. This is due to the line designs ensuring that the E_{max} is below the E_c values thus, the conductors will not be running in corona. The converter losses are higher than the line costs and losses which indicate that the voltage selection needs to be carefully chosen based on whether the case being considered is in the border of two voltage levels. It should be noted that for HVDC voltage levels, the discreet voltage levels are based on standard equipment presently in use at those levels. The actual operating level of the line can be varied.

8.3.3 Optimise The Line Design

With the voltage known and the number of conductor bundle options determined, it is possible to determine the tower and conductor foundation combination that is optimal for the power transfer and line length considered.

The tower configurations are more varied in the case of HVDC than in HVAC. The poles of an HVDC line do not have to be on the same tower and the poles can be on different towers in different servitudes. Thus monopole, bipole, and tri pole are possible.

In addition to these options there are also the options of guyed vs self supporting, cross rope, mono pole or H pole etc. The foundation and total line cost will depend on these options chosen.

From this design process, it is suggested to use an indicator as derived for the AC case to objectively determine the best group of line design options.

Note that the voltage drop considerations mentioned by Singh [2005], will be automatically taken into account in the line losses cost over the life of the line.

8.3.4 Re-Check The Voltage- Line Design- Converter Combination

From the initial determination of the voltage and the converter design relating to the voltage choice, it is necessary to recheck the final design to determine whether the original assumptions are valid or not. If valid, the line design can be finalised based on detailed analysis of the final group, as indicated by the objective determination process.

8.4 SUMMARY OF OPTIMISATION PROCESS

The optimisation process for a line design given a power transfer and line length requirement is proposed as follows:

1. Determine the voltage level from either of the methods proposed by Jinhau [2009] or Nolasco [2009].
2. Determine the conductor/bundle configurations that will meet the corona level limits for the selected voltage level
3. Determine the range of tower, conductor and foundation combinations using an objective indicator (to be developed in the next chapter).
4. Once the final group of line design options have been finalised, revisit the voltage, converter, line design options to check if the options chosen are indeed valid. If not the process needs to be restarted.
5. Finalise the system design.

8.5 OBJECTIVE MEASURE AS A BUSINESS TOOL

The "objective" measure is not a means to determine, by detailed analysis, the best line design option. It is more of a business tool to enable designers to focus on a group of designs of which one option will be implemented. The term "objective" in this case implies a means to determine the group of options by means of a score rather than the "subjective" assessment of many line design options where the designers may use a "gut feel" in determining the final design option to implement.

8.6 CONCLUSION

The HVDC system design process is very similar to the AC design process even though there is an opportunity to vary the voltage level which is often not the case in AC systems. In HVDC the positive and negative poles need not be on the same tower, whereas in AC the phases need to be in close proximity. With these variables, it has been found that the voltage selection can be narrowed down and selected quite readily from work published by Nolasco [2009] and with more analysis by Jinhau [2009].

The line design options can be more varied than in the AC case which strengthens the case for an objective indicator to determine the best line design solutions.

CHAPTER 9

DEVELOPMENT OF A HVDC LINE DESIGN INDICATOR

9.1. INTRODUCTION

Based on the analysis given in Chapter 8, the line design indicator is necessary to determine the best group of tower, conductor, and foundation combinations for a given voltage level and power transfer capability.

It is intended to use the AC indicator as a base in the development of the DC indicator. The philosophy used in the AC indicator is that the main parameters that encompass the varying design are used in determining the best option.

These were identified as follows:

1. SIL (MVA SIL) covers the phase spacing, conductor bundle, bundle configuration and height above ground.
2. LCC covers the initial cost of the line as well as the cost of losses determined by the line impedance and conductor resistance.
3. IC is the initial cost of the line.
4. MVA (thermal) is the thermal rating of the line determined by the conductor bundle design and templating temperature of the line.

The SIL is not applicable for HVDC systems and another parameter is required in this case. The chosen parameter needs to take into account the effect of phase spacing (pole spacing) subconductor size, number of sub-conductors in the bundle, bundle diameter, and height above ground. This will ensure the full tower top geometry is catered for in the parameter.

9.2. DEVELOPMENT OF HVDC PARAMETERS FOR USE IN THE INDICATOR

9.2.1 Replacement Of The SIL Parameter

A similar parameter in the HVDC case is the corona power loss parameter which is a function of E_{max}. The E_{max} is determined by the geometric design of the bundle and the location of the bundle in space which determines the tower design and hence, the bundle, conductor, tower and foundation combination. The aim is to have the E_{max} low in value so that the corona power loss is low, and the bundle does not operate in corona conditions.

It should be noted that the corona loss in accordance with the graph 8.3 is the lowest loss parameter. It may be questioned therefore as to why the corona loss is used in the indicator. The reason is that the corona is a constraint and, in order to remove this constraint, the optimum bundle, tower top, and conductor height needs to be determined for the particular voltage determined. The reason that the corona loss is therefore so low a percentage of the cost per year in comparison to the other components such as the resistance (line) losses is that the constraint has been met resulting in the corona power loss being low.

Thus, it is proposed to replace the SIL parameter with the corona power loss which is not only a function of E_{max} but also the height of the conductor in meters.

The aim of the designer, in optimising the line design, would be to obtain the lowest possible corona loss for the lowest initial cost. Thus, a ratio similar to that used in the AC indicator case would be valid in this case. However, in the case of the AC ATI, the MVA_{sil}, needs to be as high as possible. In the case of the corona power loss, the loss must be as low as possible; therefore the indicator parameter used must be the inverse of the corona power loss. Thus, in the DC case the term equivalent to 'Initial cost/MVA_{sil}' is expressed as Initial cost*$P_{losscorona}$.

8.2.1.1 Demonstration Of $P_{losscorona}$ Indicator

In referring to equations [7.11] to [7.16] in Chapter 7, the Emax is a function of the following line parameters:-

n = the number of sub-conductors in the bundle

d = the diameter of the sub-conductors

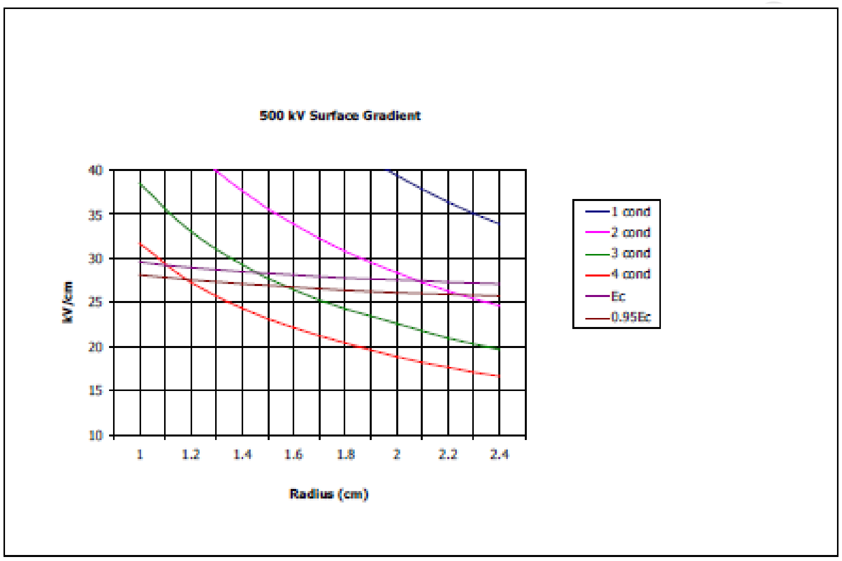
D = the diameter of the bundle

H = the height of the conductor above ground

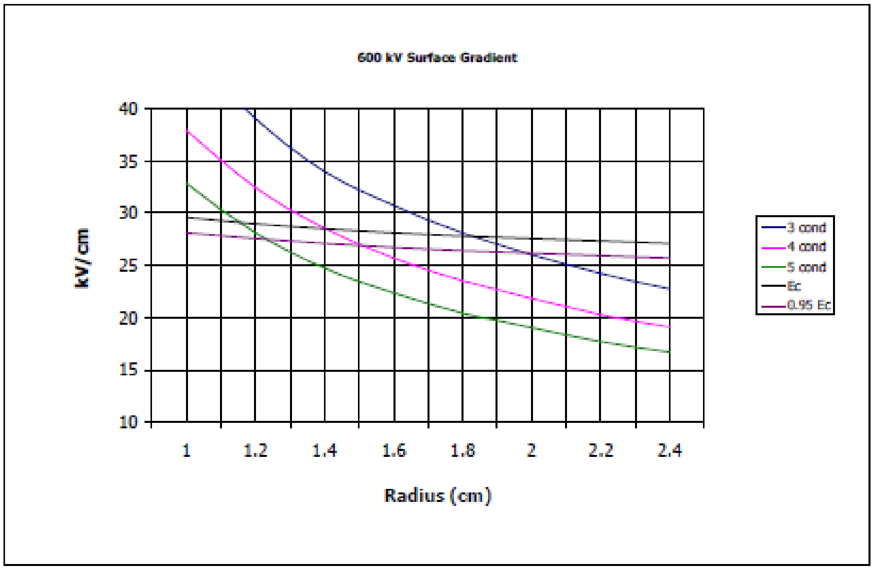
P = the distance between the positive and negative poles

S = the spacing between the sub-conductors in the bundle

It is thus possible to meet the E_{max} value so that it is at 95% of E_{crit} in many different ways. This is similar to meeting the various required SIL values in AC lines. In DC lines for example there are many different conductor options that can be used to meet the ±500 kV and ±600 kV options as shown in graph 9.1 and graph 9.2.



Graph 9.1 Different Conductor Options To Satisfy E_c For ±500 kV [Nolasco, 2009]



Graph 9.2 Different Conductor Options To Satisfy Ec For ±600kV [Nolasco, 2009]

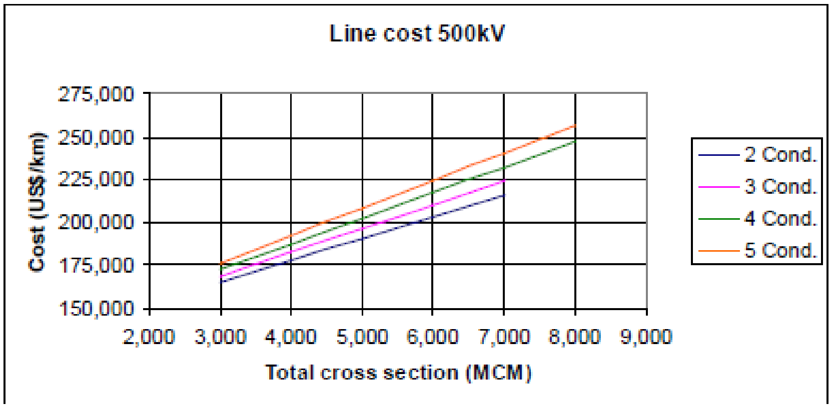
Note in the graphs 9.1 to 9.4 the conductor types cannot be identified as there could be many different types of conductor for the same radius. The graphs have been developed using American standard conductors hence the unit of area being MCM and not mm^2.

In graph 9.1 the 0.95 Ec limit can be met with 2, 3 or 4 (or more) sub-conductors in a bundle with radius of 1.2 cm or above for four conductors in the bundle and 1.6 cm radius for 3 conductors. For 2 conductors the radius of each subconductor needs to be at least 2.4 cm.

In graph 9.2 for ±600 kV the 0.95 E_c limit can be met with 3 or larger number of sub-conductors with the radius of the subconductor being 2 cm or greater for the 3 conductor bundle option.

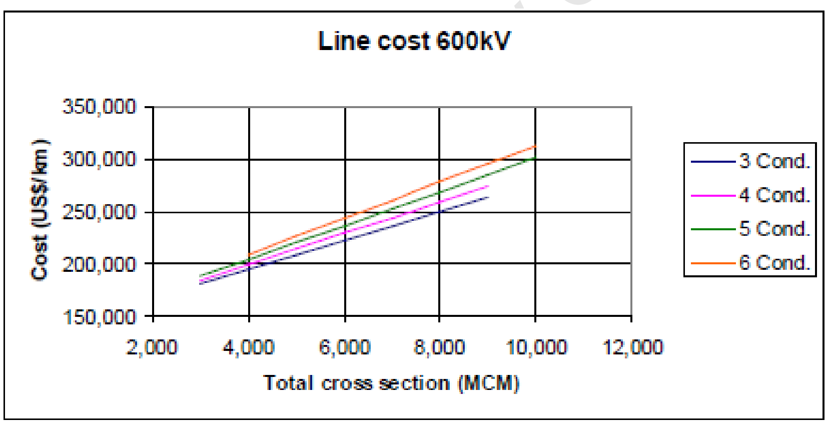
These graphs are specific for a certain conductor roughness and altitude or air density but serve as an example of the various solutions that can be used to solve the E_c limits.

Each option has a cost implication to it. In graph 9.3 the cost as a function of the aluminium area in the bundle is given.



Graph 9.3 Line Cost For Various Conductor Bundles At ±500 kV [Nolasco, 2009] MCM = 0.5067 mm^2

With reference to graph 9.3 above, the cost of the line, depending on the conductor chosen, the cost can vary from 2 conductors at 2.3 cm radius per conductor (approximately 2500 MCM or 1250 mm^2 per conductor) to 4 conductors greater than 1.2 cm radius per conductor or 1350 MCM or 675 mm^2. (Note the conductor sizes are taken from the Southwire manual [Southwire, 1994]. This relates to a line cost variation of approximately 188 000 US$/ km for the twin conductor option at 5000 MCM total or 210 000 US$/ km for the quad bundle option.



Graph 9.4 Line Cost For Various Conductor Bundles At ±600 kV [Nolasco, 2009]

In reference to graphs 9.2 and 9.4 above, for the ±600 kV case, the 0.95 E_c gradient can be met with 3 conductors at 2 cm radius or 1590 MCM or 795 mm^2 . It can also be satisfied with 5 conductors at 1.25 cm radius or 666 MCM or 333 mm^2. The total bundle size for 3 conductors is thus 3X1590 = 4770 MCM and with the 5 conductor bundle it is 3333 MCM. The cost for the 3 bundle is thus 205 000 US$/ km and the 5 conductor bundle is 190 000 US$/ km. (Conductor sizes obtained from Southwire manual [Southwire, 1994]).

It is interesting to note that the larger subconductor bundle for ±600 kV is a lower price than the smaller (3 bundle) whereas for ±500 kV the twin bundle is less than the quad bundle. It is possible that if a 5 or 6 bundle option was given for the ±500kV in graph 9.1 that this option would have been a lower cost than the twin conductor bundle option. This is because the minimum size or MCM can be smaller than the twin option for large subconductor numbers. For example extrapolating the curve for ±500 kV to 5 conductors should result in a radius of 1 cm or less being required for 5 sub-conductors. Thus a conductor of 398 MCM or a total area of 1990 MCM may suffice. This will give a cost of below 150 000US$/ km for the ±500 kV option.

Thus, from the simple exercise using the work of Nolasco [2009] it seems that the higher the sub-conductors in the bundle and the lower the permissible MCM, the lower the cost for conductor bundles above 4 sub-conductors per bundle. The minimum MCM is a function of the power transfer required and the optimum power losses which is a function of the life cycle cost.

Thus if the designer can optimise the LCC as well as ensure that the corona limitations are met with the lowest initial cost it, is likely that the line design will be one of the options to consider further.

Whilst it is possible that the indicator can use the E_{max} value for the corona term, the power loss equations in [7.18] and [7.19] combine the E_{max} value with the bundle configuration as well as height above ground. It also enables the figures to be expressed in currency values if the cost of losses is known.

It is proposed that the corona power loss is used for the indicator in the term where the power loss is multiplied by the initial cost of the line. The lower the overall term the better the option.

This term is applicable for any voltage level as the E_{max} term must be determined as part of the conductor selection. It is also possible to allow for a slightly higher corona power loss at a lower initial cost as opposed to a low power loss at a higher initial cost in the optimising process, as the term takes both corona power loss and initial cost into account.

9.2.2 Life Cycle Cost

As indicated previously, the life cycle cost is a function of the line initial cost, the corona power loss and the I^2R loss due to the power flow. This parameter is also critical as was the case in the AC analysis. The aim would be to minimise the LCC. This is similar in reducing the losses in the AC line by ensuring that the SIL is maximised for the initial cost as well as studying the network losses for the various conductor sizes. This is not "double counting" the corona loss as the concept to minimise the corona loss for any given initial cost is similar in nature to the maximisation of the SIL. The life cycle cost will ensure the optimal aluminium area in the case of DC lines with the various tower configurations.

The life cycle cost minimisation will take into account the voltage drop mentioned in Singh [2009] as the higher the voltage drop the higher the losses on the line. There is an optimum point, however, where the cost to reduce the LCC further by means of lower resistance conductor bundles will be prohibitive.

9.2.3 Thermal rating

The HVDC line can be operated at the current required by the system operators. It is not a function of the system configuration as is the case in the AC network. The line can be run up to the thermal limit if required. It is thus important to maximise the thermal rating of the line for the lowest initial cost. A ratio again can be used in this case.

9.3 HVDC INDICATOR FOR OBJECTIVE DETERMINATION OF LINE DESIGN

In determining the HVDC indicator the AC indicator can be used as a basis. The terms for LCC and the thermal rating component are common to both HVDC and HV AC. The HVDC LCC term will use the cost of I^2r losses as well as the corona losses which are smaller than the resistive losses . Instead of the SIL parameter used in the case of HVAC, the corona loss parameter can be used for HVDC.

Based on the analysis above, the following can be used as an Appropriate Technology Indicator for HVDC.

$$ATI_{DC} = w_1 LCC + w_2 IC * P_{losscorona} + w_3 \frac{IC}{MVA_{th}} \quad [9.1]$$

where

ATI_{dc} Appropriate Technology Index for DC lines

LCC is the life cycle cost expressed in terms of a score from 1 to 10 and IC is the initial cost.

$P_{losscorona}$ is the power loss due to corona.

IC is the initial cost.

$MVA_{thermal}$ is the thermal rating of the line and depends, as in the AC case, to the templating temperature of the line.

The terms in the ATI_{dc} equation are similarly normalised into a score out of 10 to ensure these terms can be added.

The weightings are determined by system operators, but as is the case in AC instance the analysis should vary the weightings and take the option with the highest ranking across all variations of weightings representing the most robust design.

9.4. APPLICATION OF THE HVDC INDICATOR

Singh [2005] provides 3 examples for ±500 kV lines with the parameters shown in Table 9.I.

In the process described in Chapter 8 section 3, the first step in the design process is to determine the optimum voltage to use. This is done using the graph in Nolasco [2009]. In using this graph Singh [2005] should have chosen 800 kV as an option. Thus the examples in the ±500 kV range, discussed below, are for example only and would suit a power transfer of 1500 MW for 3000 km.

Case	LCC (Rbn)	Losses (Rbn)	Corona Loss kW//km	ThermalL (A)
5 IEC 800	20.45	1.45	17.45	4650
5 Bersfort	18.91	1.61	17.45	4375
4 IEC 800	17.86	1.76	19.95	3720

Table 9.1 Data for Three Cases At ±500 kV

In deriving the above table, the following assumptions were made Singh [2005]

1. Aluminium costs as follows: R360/mm^2 (±500 kV), R380/mm^2 (±600 kV), R420/mm^2 (±800 kV)
2. R20/MWh was used to calculate the cost of losses

The losses include the corona loss which was calculated as an average of the fair and foul weather conditions. The life cycle of the asset was assumed to be 25 years

From the above the following ratios and scores are calculated for Table 9.2. It is assumed for the scores that the 5 IEC 800 conductor case is the base case with a score of 3.

Case	LCC	Corona*IC	IC/MVA_{TH}
5 IEC 800	3	3	3
5 Bersfort	4.03	4.3	3.52
4 IEC 800	4.73	3.78	2.94

Table 9.2 Scores For Ratios

In deciding that the IEC 800 is the “normal or present” practice with a score of 3/10, one point on the curve is then fixed. It is necessary to decide on the other point in order for the line equation to be derived.

For LCC the score of 10 was assumed for a LCC of R10bn (negative slope as the lower the better). For the corona loss ratio a value of 100 (RkW/ km) (negative slope) was taken as a score of 10 and for the thermal rating a value of 500 (Amps/Rand) was assumed to obtain a score of 10. Note that although the assumptions for the score of 10 are fairly random the overall comparison of the scores of the different options is still valid as the same scoring curves are applied to all cases.

Using the above scores, the weighting factors were varied, giving the results shown in Table 9.3.

Case	0.8,0.1,0.1	0.4,0.4,0.2	0.2,0.4,0.4	0.1,0.1,0.8	0.1,0.8,0.1	0.4,0.2,0.4
5 IEC 800	3.00	3.00	2.99	2.99	3.00	3.00
5 Bersfort	4.01(2)	4.05(1)	3.94(1)	3.65(1)	4.21(1)	3.88 (1)
4 IEC 800	4.46(1)	4.00(2)	3.64(2)	3.21(2)	3.79	3.82(2)

Table 9.3 Varying Weighting Factors And Ranking (Brackets)

Table 9.3 indicates that the option 2 of 5 Bersfort conductors, ranks as the best option for the wide range of weighting factors and it can be concluded that this could be the best option. In this case the life cycle cost option gives the option 3 as the best option. Thus, if LCC is the main criteria for the utility this option may be chosen. However, the best result as a function of the initial cost is the option 2.

9.5. CHOICE OF WEIGHTING FACTORS

The weighting factors were initially intended to be determined by the planners who would know the purpose of the line and can therefore determine the best set of weighting factors for the particular line in question. This, however, was found to be difficult in practice as the planners were unsure of the factors to use. This is due to the uncertainty of the loads in the future, the location of generation plant, the exact network configuration in the future and so on. A robust line design is thus required to cater for the many alternative scenarios likely to be realised.

The following procedure is thus recommended:

- That a wide range of weighting factors is chosen and the overall score and ranking for each option is determined.
- From the rankings obtained for each of the weighting permutations, the options with the highest average ranking can be selected for further investigation. More than one option should be taken forward for the detailed design phase.

Note that the indicator is a means to assist the designers to narrow the options objectively, but will not determine the only option as the designers and planners then need to investigate the design option in the specific case looking at all aspects such as terrain, landowner requirements, maintenance preferences, etc. From all these aspects a decision can be taken as to the most appropriate line design.

9.6 COMPARING AC AND DC LINE OPTIONS

The HVDC and AC appropriate technology indicators (ATI_{dc} and ATI_{AC}), are similar in nature and it should be possible to compare, objectively, the best option for a point to point load transfer using the indicators.

This can be done by examining the two equations:

$$ATI_{DC} = w_1 LCC + w_2 IC * P_{losscorona} + w_3 \frac{IC}{MVA_{th}} \quad [9.1]$$

$$ATI_{AC} = w_1 LCC + w_2 \frac{IC}{MVA_{sil}} + w_3 \frac{IC}{MVA_{th}} \quad [6.1]$$

It is possible to directly compare the LCC and MVA_{TH} terms. The terms referring to MVA_{SIL} and $P_{losscorona}$ which are specific to the nature of AC and DC transmission cannot be directly compared.

In comparing the benefits of AC and DC transmission there are a great number of other factors such as the use of the device in the network, tee off requirements, load and generator characteristics, etc. Thus the network choice of AC or DC is normally a decision taken by the planners long before the line designers become involved. However, it is possible to compare, using the LCC and thermal components, the benefits of the choice of AC or DC in relation to the line design only. Thus it may be possible to show the in the DC case the LCC is more or less beneficial than in the AC case. This may only provide one parameter to the planner in his decision as to whether to opt for a DC or AC link.

The use of the indicators is therefore geared more towards the selection of design options once the decision as to whether the system to use is AC or DC has already been taken.

Once this is decision is made and the HVDC voltage determined, the ATI_{ac} or ATI_{dc} can be used to determine the best line design options.

9.7 SUMMARY

The HVDC line design indicator developed is very similar to the AC indicator with the same philosophy being used in that the $P_{losscorona}$ and the MVA_{SIL} cover the main design aspects of the line. Thus, the bundle design, conductor selection, and pole configuration, and phase location in space is captured in this one parameter. The initial cost encompasses the tower, foundation design and ease of construction. Thus, the $P_{losscorona}$ or the MVA_{SIL} terms give the best combination of initial cost and SIL or corona power loss.

9.8 RELIABILITY AND OTHER FACTORS (AC AND DC CASES)

In the case of line design, the reliability level as well as the lightning performance is also added into the design. These factors are not directly taken into account into the ATI.

In the case of wind loading, the designer will use a certain wind load for a certain line based on the reliability criteria for the line (level 1, 2 or 3 in the case of IEC [2003]). In addition there may be certain strengthening of tower members to increase the resistance to tornado and other narrow fronted gusts directly onto the tower.

For ease of construction it is also possible that members will be designed to be interchangeable. This will be reflected in the ATI in a slightly higher manufacturing cost and lower construction cost. The overall benefit may be a lower initial cost which is included.

Factors such as wind load are common to all the line design options as is clearance and therefore are not included in the ATI specifically. The type of tower chosen will react to the wind loading in different ways. For example, the cross rope suspension tower with a very small tower face may be able to withstand the wind load with very small increase in the tower weight and hence, the initial cost will be lower for this type of tower than a self supporting tower. Thus, the ATI will take into account the initial cost which is a function of the tower type and the ability of that tower to take certain loadings.

A similar argument can be applied to lightning performance of the line. In the case of the cross rope tower with a negative cover angle (all three phases are inside the spacing of the shield wires), the lightning performance is better than towers with a positive angle. In the latter case, it will be necessary to increase the tower height to realise a similar lightning performance. This will be reflected in the initial cost of the line and thus will be accounted for in the ATI.

There are other factors, such as maintenance and reliability, due to conductor diameter to weight ratios that may result in erratic movement. In these cases, it is not always possible to design the factors into the line so that they are represented in the initial cost. In these cases, it may be prudent to use these as “gate keepers” as mentioned in the previous chapters on the AC ATI.

If maintenance requirements, such as live line as well as helicopter access, are a requirement up front, the ATI will function correctly as the tower designs will be compliant and the lowest initial cost that meets these criteria will score well.

9.9 CONCLUSION

In conclusion it is apparent that the ATI concept will take into account the majority of the line aspects, such as maintenance, constructability, reliability (as gatekeeper or in the initial cost), as well as function. The ATI_{dc} is used after the HVDC voltage has been determined using Nolasco [2009]. Similarly the ATI_{AC} is used after the voltage is determined.

Due to the number of factors that need to be taken into account in deciding whether to adapt the AC or DC option, the ATI's cannot be used for comparison of AC or DC transmission, but can indicate which is the best set of AC line options or DC line options to pursue further.

CHAPTER 10

HYPOTHESIS TESTING

10.1. INTRODUCTION

As mentioned in Chapter 1, the hypothesis, that the indicator (ATI) does in fact aid optimisation of lines by readily identifying the best group of options, and allows for a more effective line optimisation to be realised, then has to be tested. The method of testing at this stage involves studying the line design process utilised in utilities at present, showing the benefit of the approach using the indicator and thereafter indicating the benefit of the indicator in the optimisation process.

10.2. TESTING THE HYPOTHESIS

The hypothesis as proposed in Chapter 1 is as follows:

It appears that one or a small set of appropriate technology indicators can be used by network planners and designers to identify the best group of overhead lines to meet specified objectives. These indicators can be used for a wide range of applications for AC and DC lines.

In testing the hypothesis it is prudent to look at examples covered and determine whether it would be possible to determine the optimum group of designs that will meet the function for which it is intended, without any indicator.

10.2.1 Purpose Of The ATI

The ATI's developed for both AC and DC lines will enable the designers to determine the best set of line design options for further in depth analysis. It is not a tool that will, by multi-criteria analysis, determine the optimum line design for a particular function or purpose. It is therefore not an "objective" measure in the mathematical sense where a single solution can be found in all cases after detailed analysis, it is more a business tool which will enable designers to focus in on a set up line design options from which a final design can be selected for implementation.

The intent is to have simple indicators for which values can be easily determined from the analysis normally performed in the process of designing a line.

10.2.1.1 Limitations Of The Indicator

It is a comparative indicator and will indicate the best options from a group of design options considered. It will not indicate what designs have NOT been considered. For example in the case covered in chapter 5 where 11 options are considered all of these options are considered using one tower type (in this case the 529A cross rope suspension tower used in Eskom). The designers felt that this tower had been proven in the past and therefore did not consider any other family of towers. In the example on the "Camden Duhva" line shown in Chapter 6, and referenced in Stephen [2004], various tower families are considered which will lead to a better overall design being realised.

The indicator also assumes that reliability, constructability, and maintenance factors have been taken into account with the proposed designs. It is for this reason that the indicators are not meant to determine the best line design without any further analysis being done. The indicators are there to indicate the best overall design options, which can be explored further taking all aspects, such as reliability, etc. into account. Note that the initial options must take standards into account, such as in IEC [2003] where wind loading is determined. The reliability considered in the final group of designs will be for the specific terrain, atmospheric conditions (for instance lightning and ice) and maintenance practices present in the geographical area for the line. These are detailed investigations for the specific line design.

The ATI for AC and DC do not take all aspects into account and some aspects, such as use of conductors with high diameter to weight ratios, may need to be included in the form of gatekeepers due to the possible excessive movement due to wind of the conductors as explained in Chapter 5. Thus, if certain ratios of conductor types are in excess of certain values (listed in Chapter 5) they should be excluded from the options considered unless other mitigating measures are taken into account, such as heavier conductors used in jumpers or jumper weights being attached. This can then be included in the options and the ATI will take this into account in the initial cost.

10.2.2 Narrowing Design Options With Use Of The ATI

10.2.2.1 AC Case Studies

In the case shown in tables 6.1 and 6.2 in chapter 6, there are 11 different options chosen to meet the function required of the line. Without some sort of analysis it is extremely difficult to determine the best group of designs that will meet the functional requirements optimally. The analysis proposed by Vajeth [2004] was discussed and it was stated that it did not cover all aspects including the "bang for the buck" which the ATI_{AC} did in terms of the ratios to initial cost.

With the ATI_{AC} the best group of options are readily accessible in that the MVA_{SIL} and initial cost as well as MVA_{TH} ratios determine the best options as a function of initial cost. This was after the 11 options were determined via the line design process discussed in Chapters 4 and 5.

The optimisation process can be conducted for any line design option. For example in the situation in Switzerland, towers are positioned to accommodate another conductor should the load require it. In this case the indicator can be used to determine the best set of options for the 3 conductor option to allow for optimised tower designs and conductor selection for the final state.

In relation to cost saving in Eskom South Africa the indicator was used on a line previously determined as quad "zebra" by the planners. The final design option was twin "bersfort" as the planers had chosen a "standard" solution without optimising the design in terms of load and impedance. The resultant saving in the line was in the order of 30%.

10.2.2.2 DC Case Studies.

The analysis in Chapter 9 indicates that there are many different design options that can be considered to meet the corona and power transfer criteria of HVDC lines. The determination of the best options to perform detailed analysis on is very difficult without some form of indicator that shows the best design options from a life cycle, corona loss and the thermal rating for the lowest initial cost.

In the case of DC as studied in the ±500 kV DC case in Singh [2005], the 3 options discussed could not be readily assessed without the aid of the ATI_{dc}. The ATI_{dc} immediately showed the option 2 as the best option over a wide range of weighting factors. If more options were available for analysis it would identify a group of options for further study and perhaps implementation. Singh [2005] did not examine multiple options for ±600 kV or ±800 kV that could be compared with the ATI_{dc}. The work of Nolasco [2009] indicated that the best voltage option for Singh [2005] to consider is ±800 kV. Thus, the ±500 kV options were for a lower power transfer option.

In the case of the DC ATI, the voltage of the line is not part of the line optimisation as work performed in Nolasco [2009] indicate the voltage that should be used for a certain line length and power transfer. This work by Nolasco [2009] takes into account the power, length and terminal equipment to derive the likely optimal line voltage. The ATI_{dc} thus will optimise the line for the particular voltage chosen. This is in contrast to the approach by Singh [2005] where he attempts a number of different voltage levels to determine the optimum line design. It is very difficult to determine the optimum voltage, line design for a power and line length with one indicator, hence the proposal for a 2 staged approach, the first to determine the voltage and then to determine the optimum group of line designs based on the given voltage.

The voltage determination follows the standard voltage equipment levels present. That is for ±500 kV, ±600 kV, ±800 kV. Once the voltage level relating to standard equipment is determined the optimal voltage can be obtained by varying the voltage of the terminal stations. Due to the equipment being standard, however, it is unlikely that a voltage, other than the standard voltages will prove more economical as the terminal equipment costs are fixed.

Based on the above and the case studies investigated, it can be stated that the ATI’s developed for AC and DC will definitely assist in narrowing the line design options proposed to a group of optimum designs from which the detailed design can commence and the final design combination decided upon after all factors, not included in the ATI, such as land owner requirements are taken into account.

10.2.3 Actual Implementation of Indicator

The case study examined in Chapter 6 (section 6.1) dealing with the Camden Duhva line, the current design was the quad Zebra conductor guyed vee tower design. Due to analysis possible by the ATI_{AC}, the design was changed to the Cross Rope Suspension tower with the triple Bersfort design. This design proved to enable more power transfer with a lower initial and life cycle cost.

In this particular case the saving from a life cycle point of view (25 years) was R23m which justified for the use of the indicator.

The line was actually built in 1992 and has proved to be reliable and satisfactory.

10.3. RESEARCH QUESTIONS

The following research questions were raised in Chapter 1:

1. How do planners specify their objectives for a proposed line?
2. What approaches are used elsewhere to "optimise" line planning and design, and how effective are those approaches?
3. What are the key parameters that need to be taken into account for determining the best group of designs for a particular function or purpose relating to AC lines?
4. What are the key parameters that need to be taken into account for determining the best group of designs for a particular function or purpose relating to DC lines?
5. How can these parameters be combined to form indicators for AC lines?
6. How can these parameters be combined to form indicators for DC lines?
7. What is the best method/process of objectively optimising lines?
8. What feedback can demonstrate the validity of the results of the combined indicator/s?

The following responses to the questions are given below:

1. How do planners specify their objectives for a proposed line?

This was covered in Chapter 4 section 2 and is covered by Stephen [2004].

2. What approaches are used elsewhere to "optimise" line planning and design, and how effective are those approaches?

The literature Survey in Chapter 2 indicated that there is very limited literature and studies where the planning and design requirements were covered. Vajeth [2004] described the planning requirements and the integration of the line design with the planning requirements. This was also mentioned by Stephen [2004].

3. What are the key parameters that need to be taken into account for determining the best group of designs for a particular function or purpose relating to AC lines?

This was discussed in Chapters 3, 4 and 5 with the indicator being developed in chapter 6. It was found that the life cycle cost needs to be taken into account as a stand-alone indicator. The other factors, such as SIL and MVA_{TH} are considered in terms to determine the "bang for the buck". The SIL term takes into account the full tower top geometry and is thus an excellent measure of a number of design decisions. These include the conductor type, number of sub-conductors in the bundle, the bundle diameter as well as phase spacing. Chapter 4 dealt with the process to optimise the overall line design in order to meet the planner's requirements.

4. What are the key parameters that need to be taken into account for determining the best group of designs for a particular function or purpose relating to DC lines?

Similarly for DC lines the parameters were described in Chapter 7. These include the power loss due to corona which can be related to the SIL calculation as this parameter covers all the design decisions found in DC tower top geometry. This includes the number of sub-conductors, the bundle diameter, the tower type, pole distance etc. The optimisation of the DC lines was covered in Chapter 8.

5. How can these parameters be combined to form indicators for AC lines?

This was dealt with in Chapter 6 where the ATI_{AC} was developed. This followed the work proposed by Stephen [2004] and included the life cycle cost, the SIL and MVA_{TH} as a function of initial cost to indicate the "bang for the buck" obtained by the relevant design

6. How can these parameters be combined to form indicators for DC lines?

This was covered in Chapter 9 where the ATI_{dc} was developed. This was not developed previously in literature and will enable the designer to determine the best group of design options to develop further after determining the voltage of the line from the work done by Nolasco [2009].

7. What is the best method/process of objectively optimising lines?

The process needs to integrate the line parameters as well as to ensure the planners' requirements are met in the final line design. This involves an iterative process whereby the planner will conduct numerous load flows to determine the system losses and power flows with various line design configurations. This is done under normal and contingency conditions. It was found in the literature research that there was a large amount of work performed on component optimisation but not on the line design itself. Chapters 4 and 8 cover the proposed best method/process for optimising line designs for AC and DC voltages respectively.

8. What feedback can demonstrate the validity of the results of the combined indicator/s?

The feedback given in relation to actual line designs was the Camden Duhva line as well as the 400 kV line in the Eastern Cape Province that explored the different indicators as proposed by Vajeth [2004] and Stephen [2004]. A version of the indicator proposed by Stephen [2004] was used for AC. The Camden Duhva line developed resulted in new towers being developed and new conductors used. This saved around R23m over the life of the line (analysis was performed in 1992).

The DC indicator was used to indicate the best option of 3 of the ±500 kV line options used by Singh [2005]. It indicated that it could be used for the DC line design choices but that more examples are required to fully realise the benefit.

10.4. RESULTS OF THE HYPOTHESIS TESTING

From the above it appears that the hypothesis is valid. Line designs can be objectively prioritised by using indicators for AC and DC lines. It is not considered possible to use the same indicator for both AC and DC lines.

10.5. FUTURE WORK AND DEVELOPMENT

The main drive for the future work is to use the indicators in determining the optimum range of line designs. If there is a standard initial design chosen, it should be possible to compare ATI scores across utilities. The high score ATI's can be studied to understand how the utility obtained the high score.

10.5.1 Weightings

Due to the difficulty in determining the correct weighting to use, the scores are at present calculated over a wide range of weightings. The highest average ranking across all the weighting combinations is then considered the option to use or at least investigate further.

10.5.2 Reliability

The example given in Chapter 5 of the conductors with the high diameter to weight ratios gave rise to erratic movement on conductors on the lines in question. This was not the case in all lines. The diameter to weight ratio definitely seems to play a role in the movement of the conductors that is more erratic than originally calculated.

There is need for research into the movement of conductor bundles with high diameter to weight ratios to determine whether these conductors should be considered for use on HV lines.

There may also be different factors in the conductor make up other than the proposed diameter/weight ratio that will determine whether the conductor will result in a certain movement under wind. This also needs to be researched.

10.5.3 Maintenance

Although maintenance costs are small in relation to the initial cost and cost of losses, it is a need that the maintenance cost for different tower and conductor configurations are determined. This can assist in further refining the ATI to include maintenance costs in the LCC component for different tower and conductor configurations. This is not done at present.

10.6. CONCLUSION

The development of the AC and DC technology indicators has shown that it is possible to determine the optimum line or group of line designs by means of a number of ratios or factors being multiplied together. The method of normalising the values to a score out of 10 allows for the various factors to be combined into a single value from which the line design options can be ranked, and the best ranked group of options studied further.

The ATI for AC and DC is novel in that it provides for a method to determine, with relatively simple methods, the best group of line designs to evaluate in detail. In addition, the method links the requirements of the planners to the line design to ensure that the purpose or function of the line meets the planner's requirements.

The AC ATI has been used since 1992 and resulted in a change of the standard design and conductor selection for the Camden Duhva 400 kV line in Eskom, South Africa. This resulted in a saving of R23m (approximately USD 3.5m) over the life of the line. It was published in 2004 [Stephen, 2004]. In this case the line design developed produced more "bang for the buck" than the existing solution. The ATI_{AC} indicator has thus proven to be valid and can be used in a practical sense.

The DC ATI has not been previously developed and is new to the industry. This will enable benefits to be realised by analysing various design options for DC lines. With the cost of DC terminal equipment being reduced the use of HVDC as an option for planners is increasing. It is foreseen that the ATI_{dc} can add value to the design process in ensuring that the line portraying the lowest life cycle cost together with the optimum phase configuration and thermal rating can be chosen for use.

In conclusion the use of the indicators can have a major benefit to the line design industry and process in the future.

10.7 NEW TECHNICAL WORK

The new work described in this thesis is the analysis of the previous work documented by Stephen and referenced in the thesis as well as other work on indicators. The work on the HVDC indicator is new and not documented or used in practice other than in the thesis. The comparison between AC and DC indicators is also new technical work as is the proposed use of the indicators.

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APPENDIX 1

A1.1 DETAILS OF CONDUCTORS REFERENCED.

The following table details the conductors referenced in the thesis.

Conductor	IEC 61089 Code	Overall Diameter mm
Penguin	107.22-A1/S1A-6/1/4.77	14.31
Wolf	158.06-A1/S1A-30/7/2.59	18.13
Pelican	242.31-A1/S!A-18/1/4.14	20.70
Kingbird	323.01-A1/S1A-18/1/4.78	23.90
Tern	403.77-A1/S1A-45/3.38+7/2.25	27.00
Greely	469.6-A2-37/4.06	28.14
Zebra	428.88-A1/S1A-54/7/3.18	28.42
Rail	483.84-A1/S1A 45/3.70+7/2.47	29.59
Rubus	586.9-A2 61/3.50	31.50
Bluejay	565.49-A1/S1A-45/4.00+7/2.66	31.98
Bunting	605.76-A1/S1A-45/4.14+7/2.76	33.07
Grackle	602.79-A1/S1A-54/3.77+19/2.27	33.99
Bittern	645.08-A1/S1A 45/4.27+7/2.85	34.16
Bersfort	687.36-A1/S1A-48/4.27+7/3/32	35.58
Boblink	725.27-A1/S1A 45/4.53+7/3.02	36.25
Lapwing	766.06-A1/S1A 45/4.77+7/3.18	38.15
IEC 800	800.00-A1/S1A-84/7/3.48	38.30
Falcon	806.23-A1/S1A-54/4.36+19/2.62	39.24
Chukar	903.18-A1/S1A 84/3.7+19/2.22	40.69
Kiwi	1083.5-A1/S1A 72/4.41+7/2.94	44.07

Table A1: Details of conductors referenced. [IEC 61089]

The description of the IEC [IEC61089] code is as follows:

428.88-A1/S1A-54/7/3.18: Conductor made of 54 wires of A1 aluminium and 7 wires of regular strength steel wires, with a zinc coating type A (S1A). The area of the A1 aluminium wires is equal to 484.88 mm^2

If the diameter of the aluminium strands and steel strands are different, such as in the case of Kiwi conductor, the stranding is depicted as 72/4.41+7/2.94. This means that that A1 aluminium wires are 4.41 mm in diameter and the steel strands are 2.94 mm in diameter.

A1.2 CONDUCTORS WITH SPECIALISED STRANDING, CONSTRUCTION AND MATERIALS

The following conductors are different to those mentioned in table A1 due to stranding, construction and material differences:

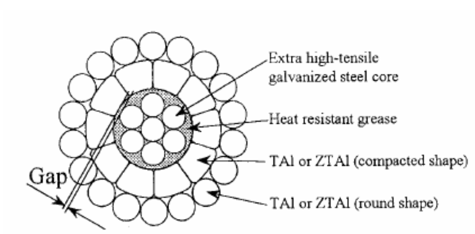


Figure A1.1 GZTACSR conductor construction [Douglass 2004]

The above Figure A1.1 indicates the construction of the GZTACSR conductor. Note that the "G" represents the gapped type, the "ZTA" represents the type of alloy and can resist temperatures to 210°C. The "C" indicates it is a conductor and the "SR" indicates steel reinforced.

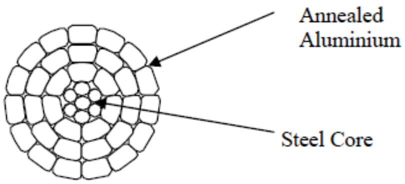


Figure A1.2 Construction of the ACSS/TW conductor

The above figure A1.2 shows the construction of the ACSS/TW conductor. The ACSS stands for Aluminium Conductor Steel Supported. The conductor is steel supported due to the fully annealed aluminium strands supporting no mechanical load. The "TW" stands for Trapezoidal Wire strands used in this conductor. The strands allow for a more compact design which reduces wind load.

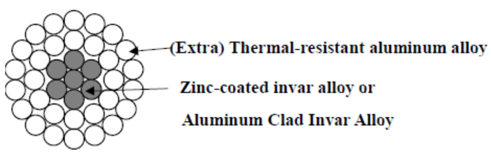


Figure A1.3 Construction of the ZTACIR conductor

The figure A1.3 indicates the construction of the ZTACIR conductor. The ZTAC has been described in the explanation of the GZTAC conductor. The "IR" refers to the zinc or aluminium coated invar alloy core (Invar reinforced). This core has a very low temperature coefficient of expansion enabling the conductor to operate at high temperatures without sagging excessively.

The following table A1.2 shows the characteristics of these conductors as shown in graph 4.3.

Conductor	ACSR	GZTACSR	ZTACIR	ACSS
Name	Tern	410	400	480 (Cardinal) ACSS/TW
Total Area (mm^2)	430.6	443.6	430.6	545.9
Alum Area (mm^2)	402.8	411.9	402.8	483.4
Outside Diameter (mm)	27.0	26.5 (-1.9%)	27.0 (0.0%)	27.5 (+1.9%)
Rated Tensile Strength (kN)	98.3	121.1 (+23.2%)	85.9 (-12.6%)	124.6 (+26.7%)
Tension @Max Load (kN)	29.7	29.1 (-3%)	22.8 (-23%)	32.6 (+9.8%)
DC Resistance @ 25°C(μ Ω/m)	73.1	74.7 (+2.2%)	74.8 (+2.3%)	59.4 (-21%)
Conductor mass per unit length (kg/m)	1.334	1.408 (+5.6%)	1.341 (+0.6%)	1.827 (+37%)
H/w @16C (m)	1625	1610	1307	1470
Cont. Operation Max. Temp (°C)	100	210	210	200
Rating (amps)*	1030 @100°C	1800 @210°C	615 @65°C	1165 @100°C

Table A1.2 Characteristics of conductors referred to in graph 4.2 [Douglass 2004]

APPENDIX 2

TOWER TYPES USED IN CHAPTER 5.

OUTLINE DIAGRAMS OF TOWERS:

515C,

515D,

515E,

515H,

517A,

517E,

517F,

518C,

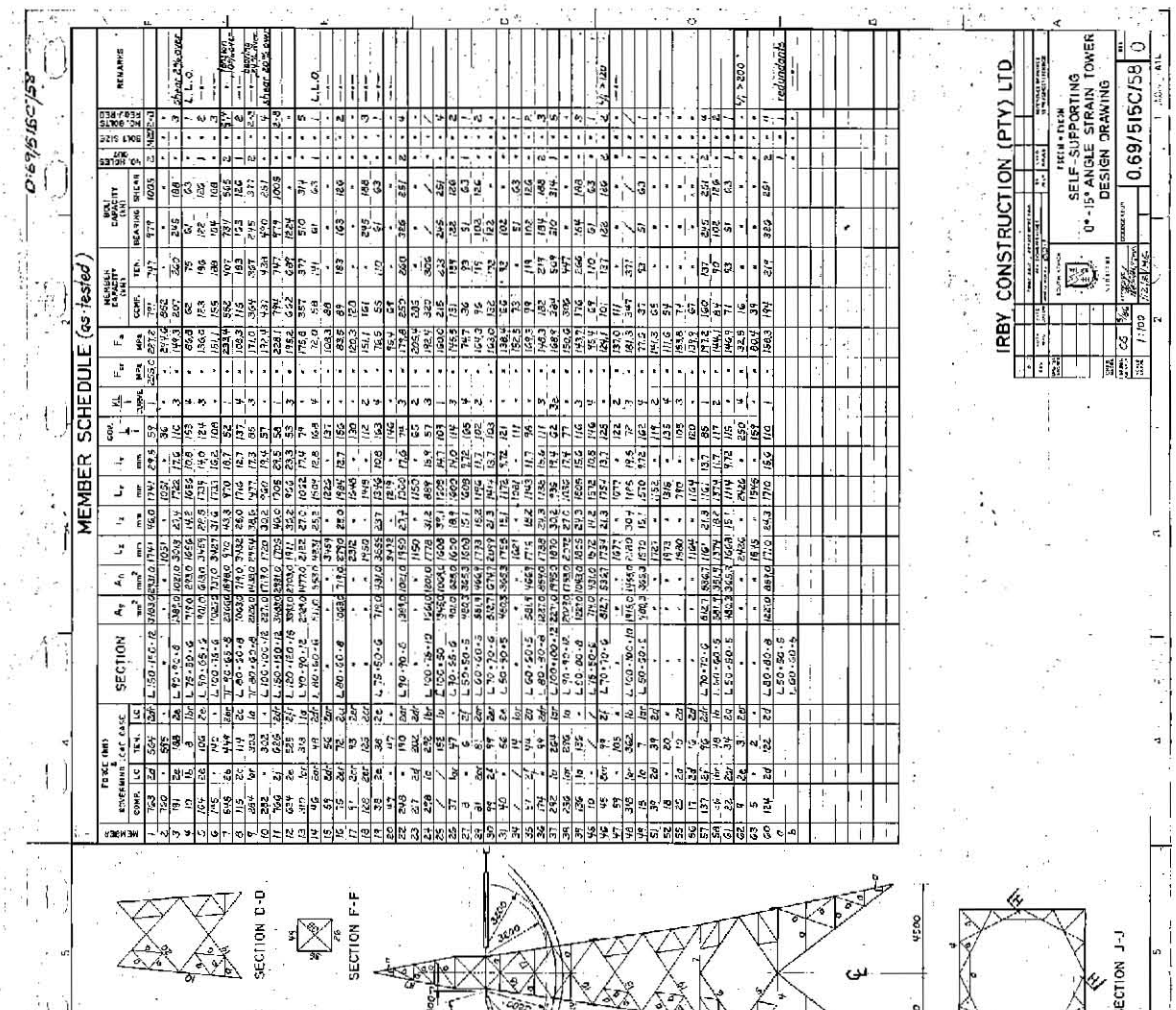
518D,

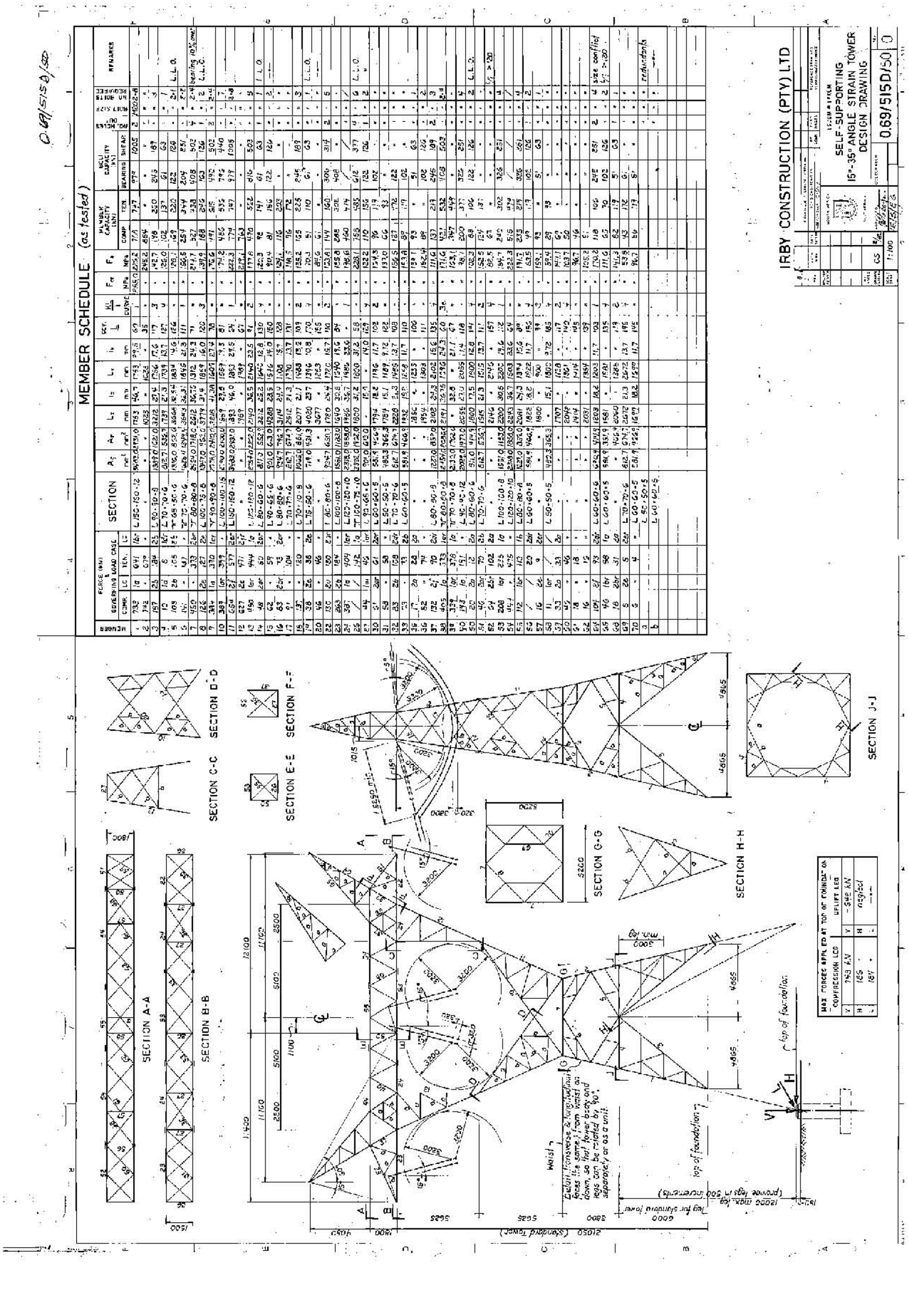
518H,

528C,

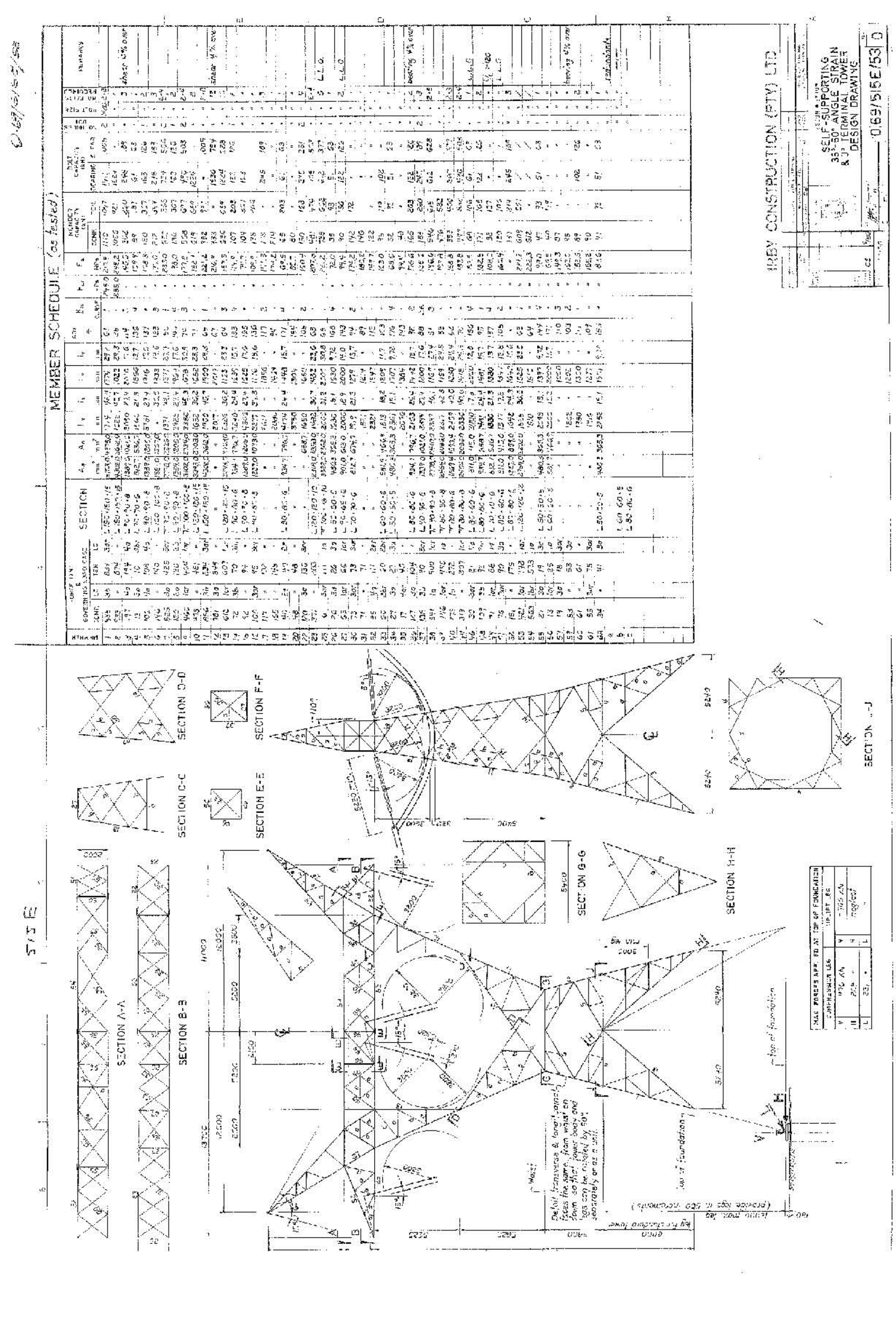
528D AND

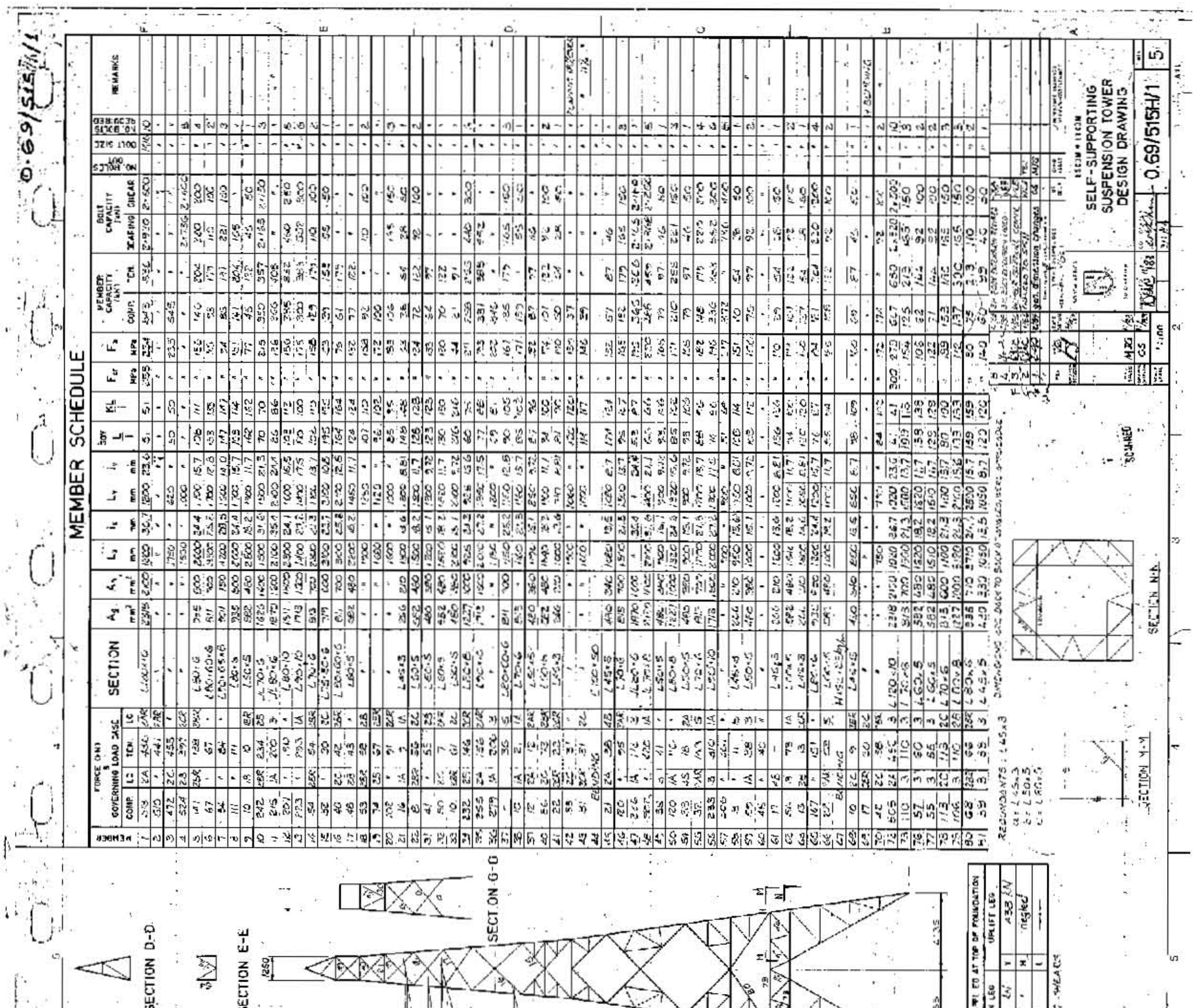
529A.

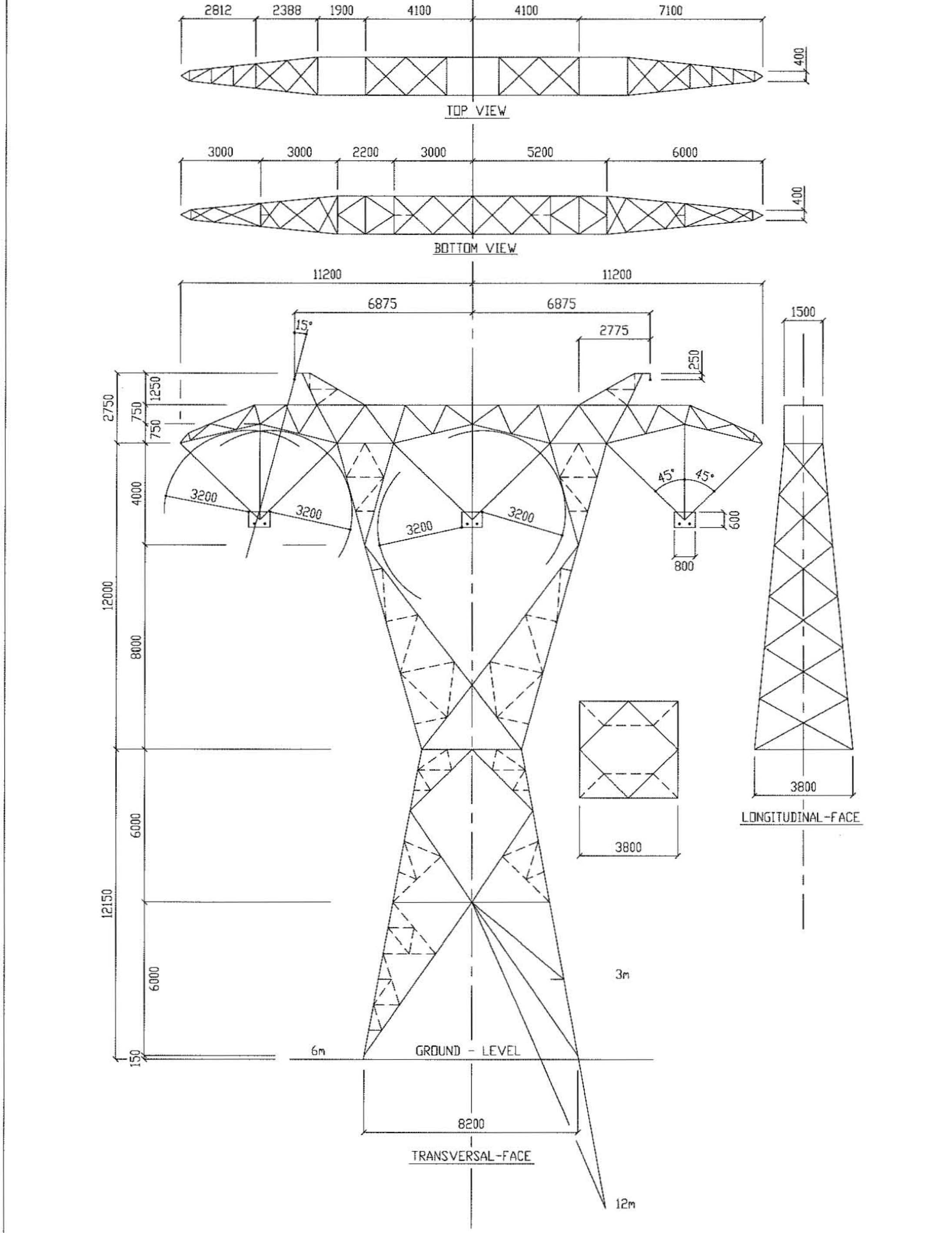

0.69/515C/58
MEMBER SCHEDULE (as tested)
SECTION A-A
SECTION B-B
SECTION C-C
SECTION D-D
SECTION E-E
SECTION F-F
SECTION G-G
SECTION H-H
SECTION J-J
top of foundation
MAX. FORCES APPLIED AT TOP OF FOUNDATION
IRBY CONSTRUCTION (PTY) LTD
SELF-SUPPORTING
0°-15° ANGLE STRAIN TOWER
DESIGN DRAWING
0.69/515C/58



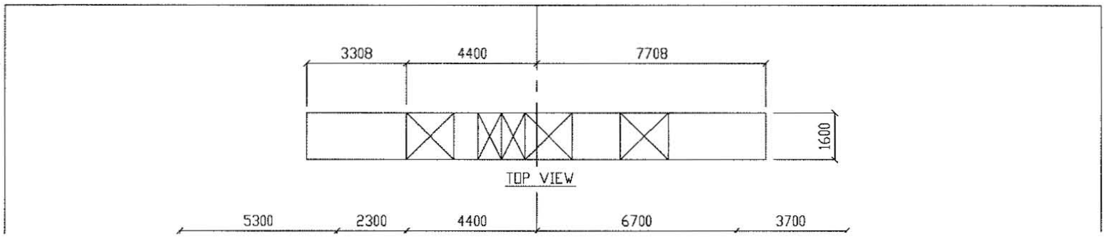
0.69/515D/50
MEMBER SCHEDULE (as tested)
IRBY CONSTRUCTION (PTY) LTD
SELF-SUPPORTING
15°-35° ANGLE STRAIN TOWER
DESIGN DRAWING
0.69/515D/50 0
SECTION A-A
SECTION B-B
SECTION C-C
SECTION D-D
SECTION E-E
SECTION F-F
SECTION G-G
SECTION H-H
SECTION J-J
MAX. FORCES APPLIED AT TOP OF FOUNDATION
COMPRESSION LCO
UPLIFT LEG
Waist
top of foundation

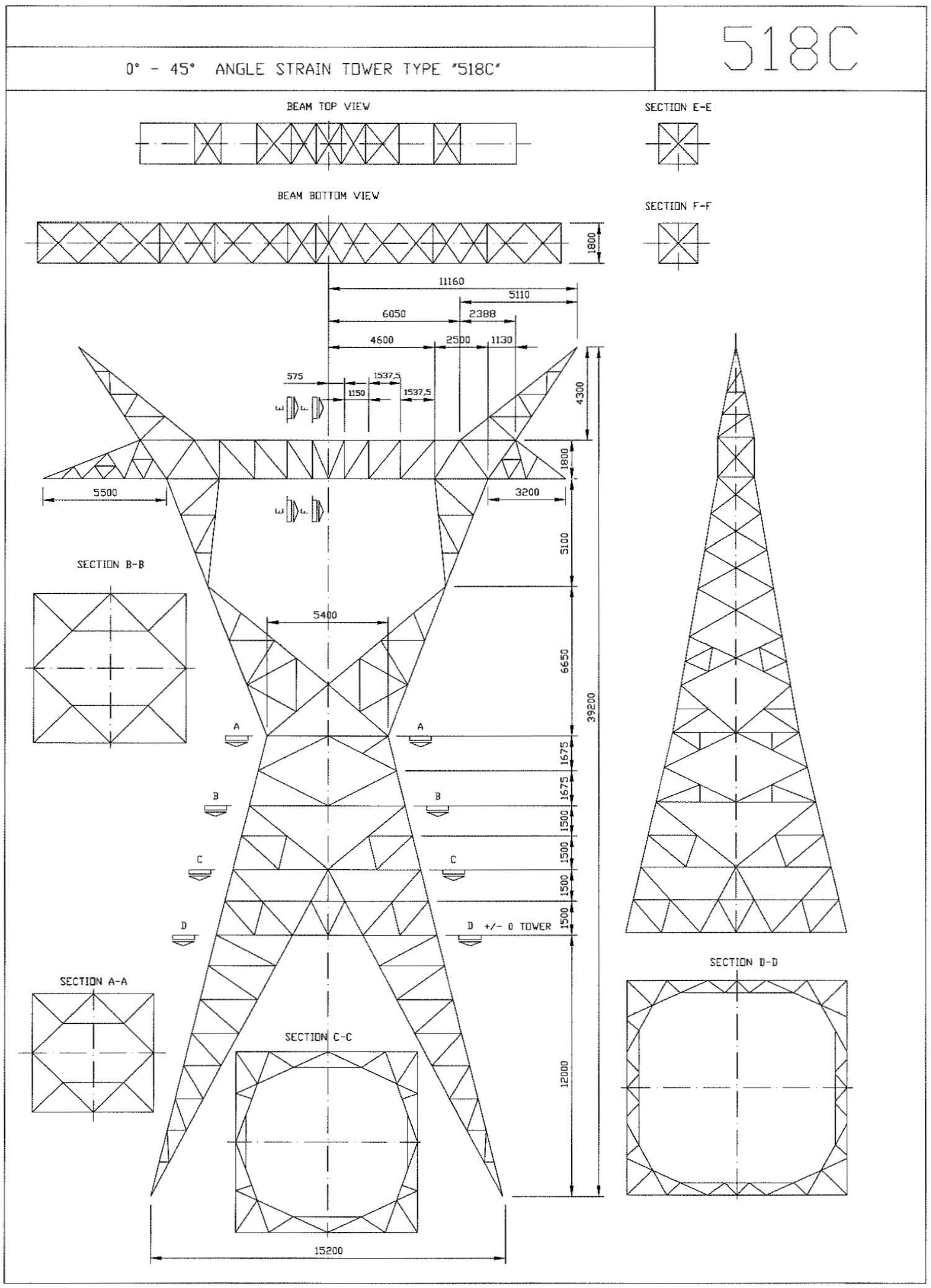

MEMBER SCHEDULE (as tested)
SECTION A-A
SECTION B-B
SECTION C-C
SECTION D-D
SECTION E-E
SECTION F-F
SECTION G-G
SECTION H-H
SECTION J-J
top of foundation
SELF-SUPPORTING
35°-80° ANGLE STRAIN
& 1° TERMINAL TOWER
DESIGN DRAWING
0.69/515E/53

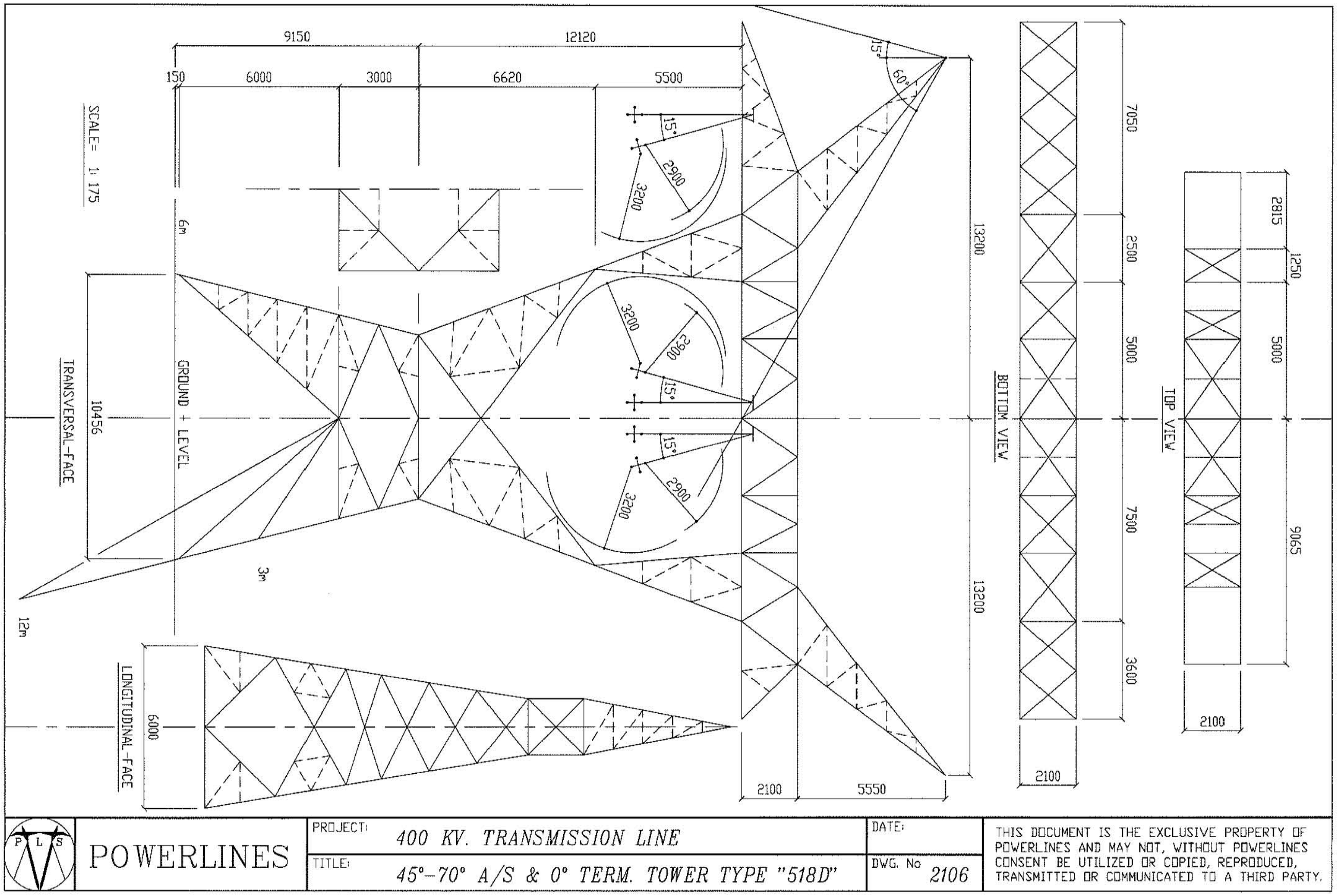

MEMBER SCHEDULE
SELF-SUPPORTING SUSPENSION TOWER DESIGN DRAWING
0.69/515H/1
SECTION A-A
SECTION B-B
SECTION C-C
SECTION D-D
SECTION E-E
SECTION F-F
SECTION G-G
SECTION H-H
SECTION J-J
SECTION K-K
SECTION L-L
SECTION N-N
SECTION Y-Y



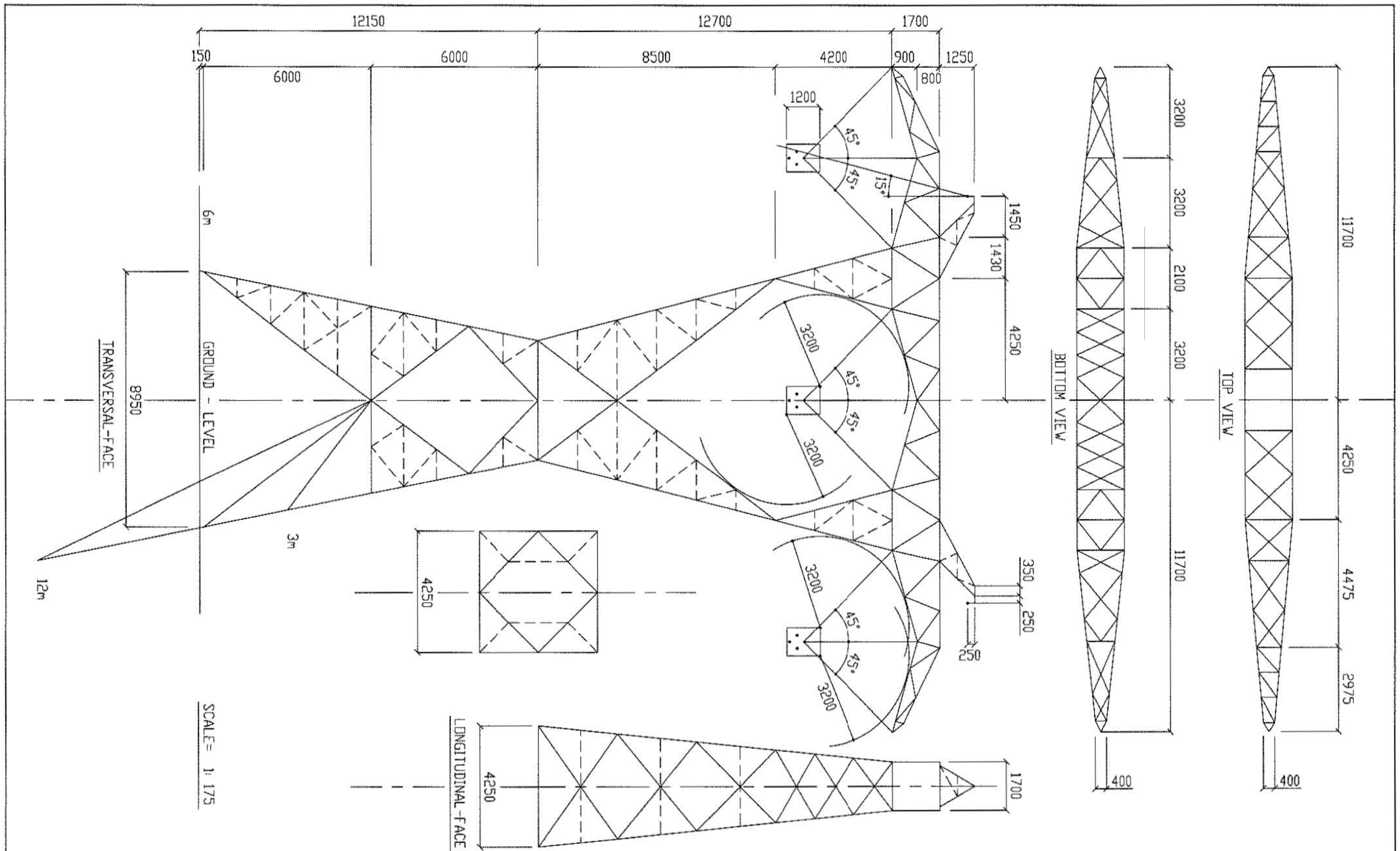
400 kV TRANSMISSION LINE
SELF SUPP. SUSPENSION TOWER TYPE "517A"


3308
4400
7708
1600
TOP VIEW
5300
2300
4400
6700
3700


0° - 45° ANGLE STRAIN TOWER TYPE "518C"
518C
BEAM TOP VIEW
SECTION E-E
BEAM BOTTOM VIEW
SECTION F-F
1800
11160
5110
6050
2388
4600
2500
1130
575
1537,5
1150
1537,5
4300
1800
5500
3200
5100
SECTION B-B
5400
6650
39200
A
1675
1675
B
1500
C
1500
1500
D
1500
D +/- 0 TOWER
SECTION A-A
SECTION C-C
SECTION D-D
12000
15200

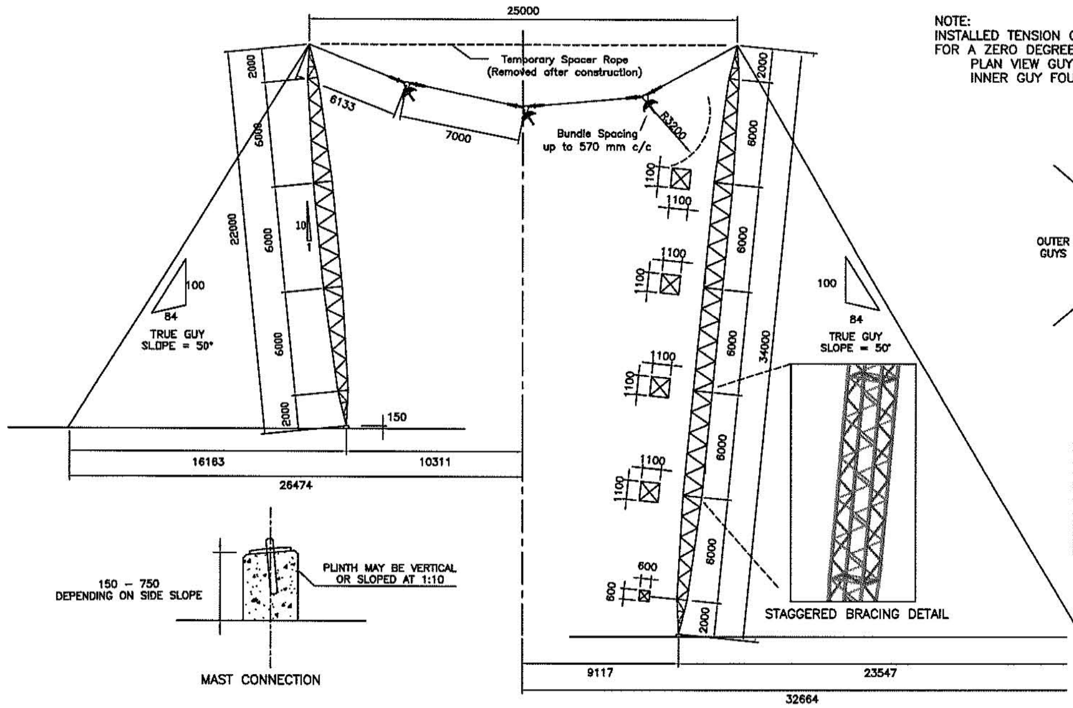


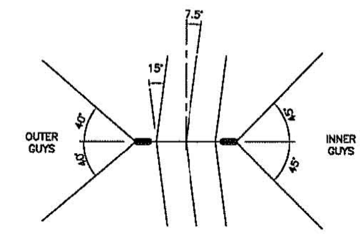
9150
12120
150
6000
3000
6620
5500
SCALE= 1:175
6m
GROUND LEVEL
TRANSVERSAL-FACE
10456
12m
3m
LONGITUDINAL-FACE
6000
15°
60°
15°
2900
3200
13200
13200
2100
5550
BOTTOM VIEW
7050
2500
5000
7500
3600
2100
TOP VIEW
2815
1250
5000
9065
2100
P L S
POWERLINES
PROJECT:
400 KV. TRANSMISSION LINE
TITLE:
45°-70° A/S & 0° TERM. TOWER TYPE "518D"
DATE:
DWG. No 2106
THIS DOCUMENT IS THE EXCLUSIVE PROPERTY OF POWERLINES AND MAY NOT, WITHOUT POWERLINES CONSENT BE UTILIZED OR COPIED, REPRODUCED, TRANSMITTED OR COMMUNICATED TO A THIRD PARTY.



POWERLINES	PROJECT: 400 KV. TRANSMISSION LINE	DATE:	
	TITLE: SELF SUPP. SUSPENSION TOWER TYPE "518H"	DWG. No 2103	

NOTE:
INSTALLED TENSION ON ALL GUYS = 31kN
FOR A ZERO DEGREE LINE DEVIATION ANGLE:
PLAN VIEW GUY ORIENTATION IS 45 DEGREES BOTH SIDES
INNER GUY FOUNDATIONS ARE INSTALLED ON BOTH SIDES





GUY ORIENTATION
PLAN VIEW

CABLE SIZES

	Min UTS	1520-1590 MPa	1400MPa
SPACER ROPE	328 kN	19mm DIA. 1520MPa	22mm DIA. 1400MPa
GUYS	610 kN	26mm DIA. 1520MPa OR 2x 18mm DIA. 1590MPa	28mm DIA. 1400MPa OR 2x 20mm DIA. 1400MPa

DESIGN DATA: 528C

EARTHWIRE	19/2.65	
CONDUCTOR	Quad Tern	
MAX WIND SPAN	550	m
MAX WEIGHT SPAN	1200	m
MIN WEIGHT SPAN	320	m
MAX SIDE SLOPE	34°	BETWEEN MAST FOOTINGS

FOUNDATION LOADS

	VERT	TRANS	LONG	ADDITIONAL LOAD FACTOR
CENTRE PLINTH	803.6	-81.2	27.8	1.1
	TENSION	GUY SLOPE		ADDITIONAL LOAD FACTOR
INNER GUYS	312.8	60°		1.3
OUTER GUYS	444.5	50°		1.4

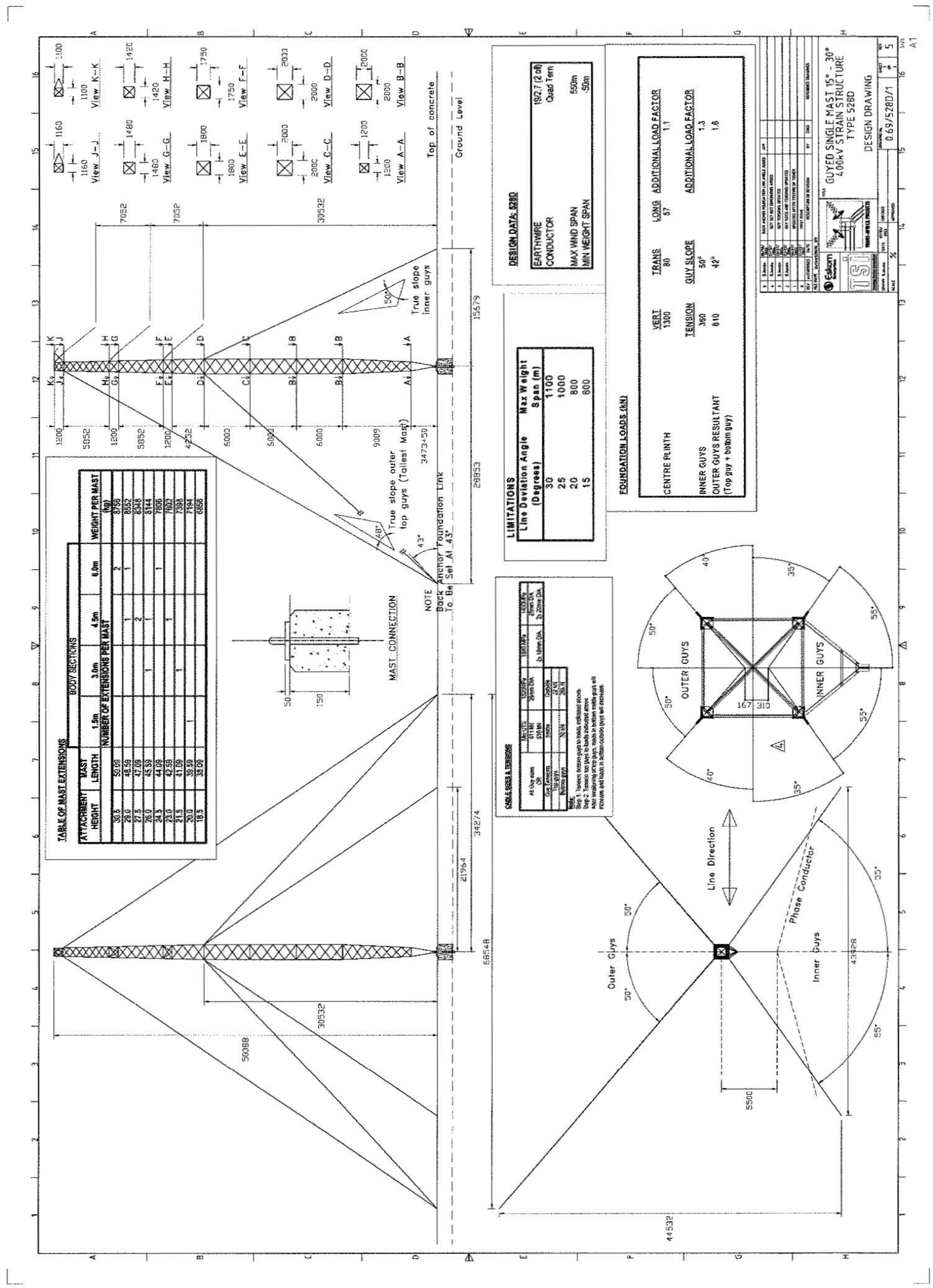
TABLE OF MAST EXTENSIONS

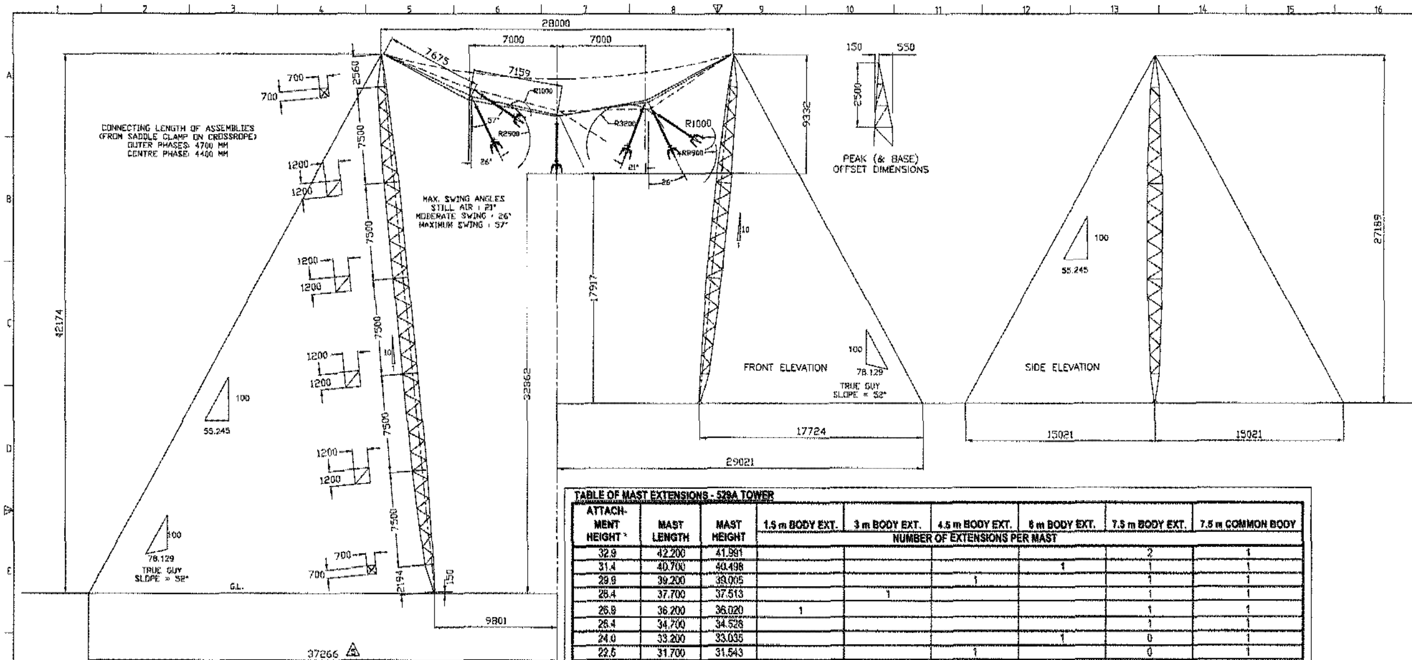
ATTACHMENT HEIGHT	MAST LENGTH	MAST HEIGHT	MAST COMPOSITION	WEIGHT PER MAST (kg)
17.2	22	21.9	STANDARD TOWER	1554
18.4	23.2	23.1	STANDARD + 1.2M EXTENSION	1687
19.6	24.4	24.3	STANDARD + 2.4M EXTENSION	1752
20.8	25.6	25.5	STANDARD + 3. 6M EXTENSION	1817
22.0	26.8	26.7	STANDARD + 4.8M EXTENSION	1883
23.2	28	27.9	STANDARD +6.0M EXTENSION	1949
24.3	29.2	29.1	STANDARD + 7.2M EXTENSION	2015
25.5	30.4	30.2	STANDARD + 8.4M EXTENSION	2147
26.7	31.6	31.4	STANDARD + 9.6M EXTENSION	2212
27.9	32.8	32.6	STANDARD +10.8M EXTENSION	2278
29.1	34	33.8	STANDARD + 12.0M EXTENSION	2343

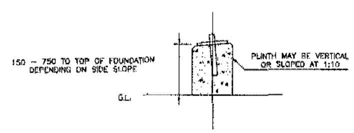
Eskom
TRANS-AFRICA PROJECTS

CROSS ROPE 0–15° STRAIN STRUCTURE 400kV TOWER TYPE 528C OUTLINE DRAWING

SCALE PROPORTIONAL
0.69/528C/1
3
A1


GUYED SINGLE MAST 15° - 30°
400kV STRAIN STRUCTURE
TYPE 528D
DESIGN DRAWING
TABLE OF MAST EXTENSIONS
MAST CONNECTION
LIMITATIONS
FOUNDATION LOADS (kN)
DESIGN DATA: 528D
OUTER GUYS
INNER GUYS
Line Direction
Phase Conductor
Top of concrete
Ground Level





MAST CONNECTION

TABLE OF MAST EXTENSIONS - 529A TOWER

ATTACH-MENT HEIGHT *	MAST LENGTH	MAST HEIGHT	1.5 m BODY EXT.	3 m BODY EXT.	4.5 m BODY EXT.	6 m BODY EXT.	7.5 m BODY EXT.	7.5 m COMMON BODY
			NUMBER OF EXTENSIONS PER MAST					
32.9	42.200	41.991					2	1
31.4	40.700	40.498				1	1	1
29.9	39.200	39.005			1		1	1
28.4	37.700	37.513		1			1	1
26.9	36.200	36.020	1				1	1
25.4	34.700	34.528					1	1
24.0	33.200	33.035				1	0	1
22.5	31.700	31.543			1		0	1
21.0	30.200	30.050		1			0	1
19.5	28.700	28.558	1				0	1
18.0	27.200	27.065					0	1

DESIGN DATA: 529A

EARTHWIRE	19/2.7	19/2.7
CONDUCTOR	TRIPLE TERN	TRIPLE BERSFORT
MAX ATT HEIGHT	32.9 m	28.4 m
MAX WIND SPAN	560 m	500 m
MAX WEIGHT SPAN	670 m	600 m
CROSSROPE UTS	321 kN	427kN
GUY WIRE UTS	321 kN	427kN
SPACER ROPE UTS	189 Kn	189kN

NOTE:
ALL DIMENSION ARE TO CENTROIDS OF MEMBERS
INSTALLED GUY TENSION = 18.0 kN
PLAN VIEW SETTING OUT ANGLE FOR ALL GUYS = 45 DEG

FOUNDATION LOADS

ALL LOADS IN kN

	VERT	TRANS	LONG	ADDITIONAL LOAD FACTOR
CENTRE PLINTH	514.0	53.8	13.0	1.1
	TENSION	GUY SLOPE		ADDITIONAL LOAD FACTOR
GUYS	260.0	52.0°		1.3

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CROSS ROPE SUSPENSION
STRUCTURE - 400kV
TOWER TYPE 529A

OUTLINE DRAWING

PROPORTIONAL

0.69/529A/1

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